ECONOMIC GEOLOGY

VOL. XXXVII NOVEMBER, 1942 No. 7

AN ENGINEERING STUDY OF GLACIAL DRIFT FOR AN EARTH DAM, NEAR FERGUS, ONTARIO.

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ABSTRACT.

The following record of some of the mechanical properties of glacial drift near Fergus, Ontario is based on soil testing carried out during construction of the Shand Dam. Mechanical testing of samples permitted the conclusion that the "clay-sized soil particles" behave as granular material. Minerological examination could be utilized to corroborate this.

THE Grand River is one of the major streams of southwestern Ontario. It has a drainage area of about 2,600 square miles; the cities of Kitchener, Waterloo, Galt, Paris, Brantford and Guelph are the main centres of population in this important section of Canada (Fig. 1). In recent years, the flow of the Grand River has caused severe flooding during spring seasons and has been correspondingly low during later months of the year, thus constituting a menace alike to property and to public health.

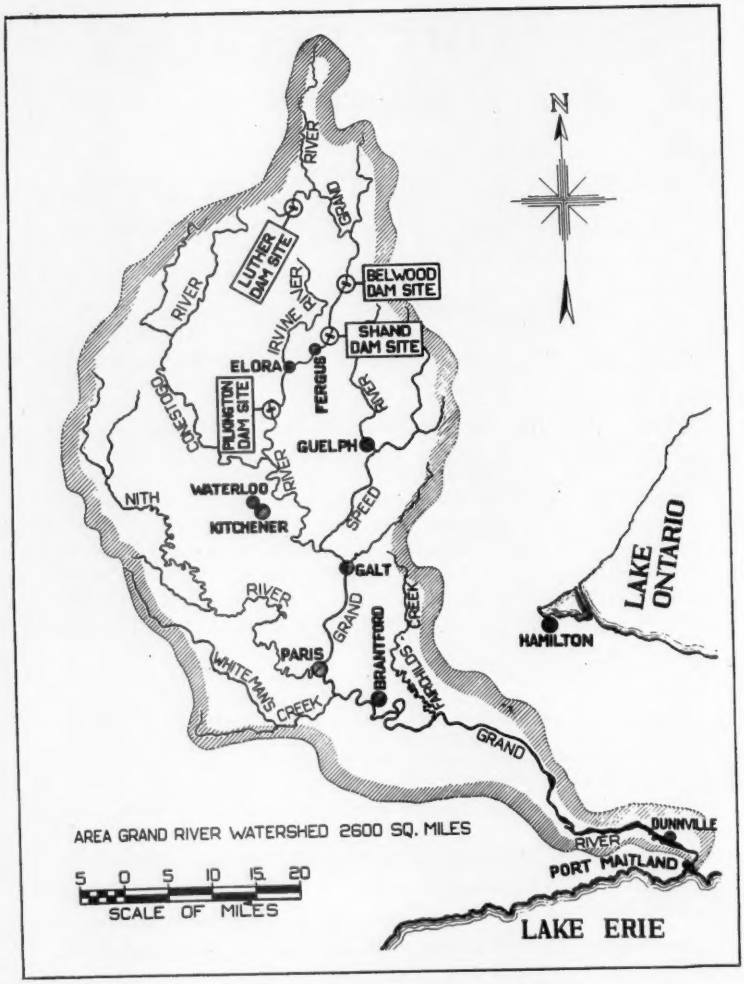


FIG. 1. The Grand River and main tributaries.

After a long period of discussion, the Grand River Conservation Commission was set up in 1938 to carry out remedial works in order to conserve the river flow. Dr. H. G. Acres was appointed Chief Engineer, and on the basis of his studies and report, construction was started in July, 1939 of the Shand Dam (located three miles north of Fergus) as the main regulating structure for the river. The dam consists of a central concrete section, supporting four steel sluice gates, flanked by earth embankments which constitute the major part of the structure, containing about 500,000 cubic yards of earth. These two embankments vary up to 75 feet in height: they were constructed by the rolled-fill method, in accordance with currently accepted practice. Based on modern soil mechanics studies, this practice requires a close control over the quality of earth used for fill, and over its moisture content, throughout all stages of construction.

Preliminary information about the soils available at the dam site was therefore necessary, to enable Dr. Acres and his staff to proceed with their designs and contract documents for the dam construction. Accordingly, in April 1939, Professor C. R. Young, head of the Department of Civil Engineering of the University of Toronto, was commissioned to undertake the necessary field and laboratory soil testing preliminary to the start of regular soil testing during construction. Professor W. L. Sagar and the writer assisted Professor Young and carried out the necessary laboratory work; the digging of test pits at the site was carried out by a local contractor.

All the unconsolidated material in the vicinity of the dam site is of glacial origin. For the soil investigations 70 test pits were dug, and sampled down to maximum depths of about twenty feet, the pits being carefully located, generally within a radius of one mile from the center of the dam. The resulting test results therefore constitute a reasonably intensive local study of glacial drift. There appears to have been very little published about the mechanical properties of the drift and so this paper has been prepared in order to make this information generally available. Results of the tests provided the basis on which the selection of

material for use in the dam was made, and upon which designs were prepared, but with these aspects of the work this paper is not concerned.[1] Results of mechanical tests on samples of the drift are included, however, since they suggest certain conclusions about the nature of the finer soil particles in the drift.

GEOLOGY OF THE DAM SITE.

The following notes by Dr. J. F. Caley of the Geological Survey of Canada are presented as describing the general geology of the area in which the Shand Dam is located.

The following remarks refer to an area of about 150 square miles which includes the site of the Shand Dam: it is traversed diagonally in a southwest-northeast direction by the Grand River and by its major tributary, Irvine Creek. The entire area is underlain by Palæozoic sedimentary rocks of which two formations are represented; these are the Guelph dolomite and the overlying Salina calcareous muds and dolomites. The rocks have suffered no major deformation and their present attitude is a fairly uniform dip averaging between 20 and 30 feet per mile in a general southwesterly direction.

With the exception of a narrow strip at the southwest corner of the area which is underlain by Salina strata the Guelph dolomite constitutes the uppermost bedrock throughout the entire region. The contact between the two formations forms a northwest-southeast trending line which crosses the Grand River about one mile northeast of Pilkington. Guelph rocks are exposed in the bed and banks of Grand River about one mile above the village of Belwood, and almost continuously from Shand Dam to about two miles below Elora. Small isolated outcrops also occur at Invernaugh and at several localities on Swan and Cox Creeks. At Elora, where Irvine Creek joins Grand River, both streams have cut a gorge exposing nearly 90 feet of the formation. In addition, exposures have been made by quarrying at both Fergus and Elora.

The Guelph rocks are light gray, buff, and brownish coloured, finely crystalline to dense and granular textured gray weathering dolomites with a small bituminous content commonly in the lower few feet of the formation. The bedding varies from a few inches to upward of 3 feet in thickness with commonly even bedding planes which may be quite smooth or rough and irregular. Some exposures show thin dark gray and greenish calcaro-argillaceous partings along irregular bedding surfaces. The

[1] For engineering details see McQueen, A. W. F., and McMordie, R. C.: Soil mechanics at the Shand Dam. Engin. Jour. 23: 161, Montreal, April, 1940.

chemical composition is remarkably uniform throughout most of the formation. Some exposures show irregular vertical jointing but this is not a conspicuous feature wherever these rocks have been seen. Small solution cavities, many lined with minute dolomite or pyrite crystals are common and in many places circulating waters have dissolved out the material filling whorls of gastropods and other fossils.

The rocks of the Salina formation underlie but a narrow strip at the southwest part of the area. Only the lower few feet of the Salina are present and since nowhere in the area are these rocks exposed, their presence is known only from test borings. As seen at the outcrop elsewhere in Southwestern Ontario and in samples taken from borings for natural gas, the Salina consists of dark gray and greenish thinly bedded and hackley weathering limy shales or argillocalcareous mud rocks with interbeds and alternating zones of brownish and gray, slaty, dense, dolomite. In the Niagara peninsula, small quantities of gypsum occur throughout the formation while farther west considerable thicknesses of Salt are present.

The entire region has been glaciated and is covered with a mantle of unconsolidated material which attains a maximum thickness of about 175 feet. As seen along the stream valleys and road cuts this overburden consists of sand, silt, gravel and boulder clay with sand and gravel probably constituting the major portion of the total. In the immediate vicinity of Shand Dam the bedrock on the left side of the river is immediately overlain by at least 40 feet of clay and boulder clay although irregular gravel and sandy lenses seem also to be present. On the right side a similar general condition prevails but with more gravel and boulders with some sand overlying the bedrock and succeeded by clay. It should be remembered that the general retreat of a glacier is in detail composed of a number of minor oscillations or advances and retreats and that such a movement may result in extreme heterogeneity of the unconsolidated deposits.

This feature of glacial deposits was clearly indicated by the records obtained from the test pits dug at the Shand Dam site.

METHODS OF OBTAINING SAMPLES.

Figure 2 shows the area in which the dam is located and the positions of the test pits dug in connection with the soil testing herein described. Pits were in general about 5 feet by 5 feet in cross-section, and were sunk wherever possible to depths of between 15 and 20 feet. All excavation was by hand, the use of picks being necessary in practically all pits except those in sand. Little timbering was required, due to the unusually compact na-

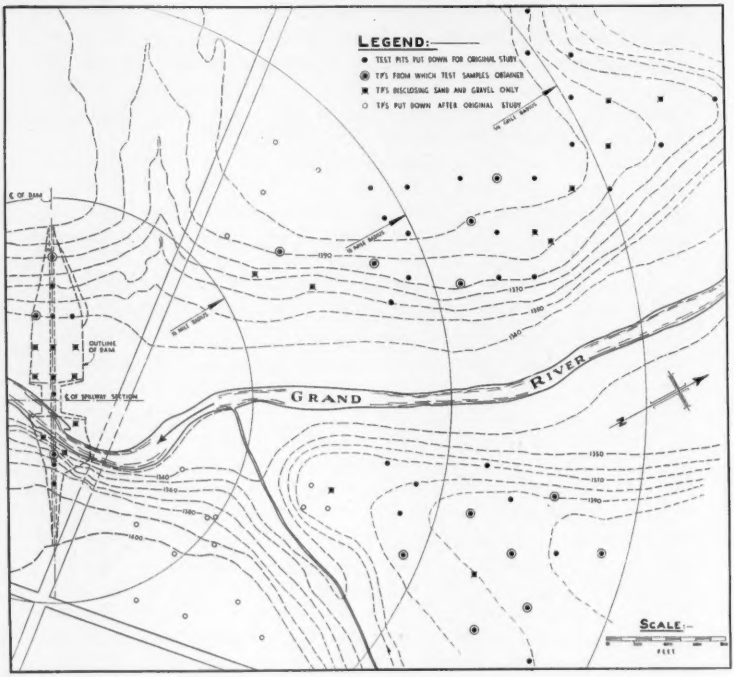


FIG. 2. Plan of the Shand Dam site, showing location of exploratory test pits.

ture of the material. One pit required the use of a steel casing, and the presence of water caused delays in a number of other cases; as the work was carried out just as the snow was disappearing, this was to be expected. Excavation amounted to 712 cubic yards, requiring 1,982 man hours of work for its execution. All pits were backfilled after inspection and sampling.

Samples, each weighing about 30 pounds, were taken at intervals of about 5 feet from all uniform material. Additional samples were taken at all noticeable changes in the soil profile of each pit. All samples were shipped to the Soil Mechanics Lab-

oratory of the University of Toronto where the soil testing was carried out. In addition to these disturbed samples, relatively "undisturbed" samples were also obtained and shipped to Toronto. These were obtained by smoothing off the bottom of a test pit and placing thereon an inverted cylindrical steel can (10 in in diameter and 12 in high). With a trowel, the soil around the circumference of the can was gradually removed, the can being steadily pushed down and encasing the cylinder of soil thus shaped. Cutting away of the soil continued after the can was full, to such a depth that the cylinder of soil could be cut off well below the lower edge of the can. After the can had been inverted, the soil was trimmed off flush with the edge of the can, the lid secured and bound up with special waterproof sealing tape. All these undisturbed samples arrived safely at the Laboratory. Careful checks showed the moisture contents of the samples when opened up several weeks (and sometimes months) later to agree very closely with corresponding moisture contents for samples tested in the field office immediately on removal from the pits. These "undisturbed" samples were used principally for investigating the shearing strength of the material which was to be left in place under the dam as part of foundation strata.

MECHANICAL ANALYSIS OF SAMPLES.

On arrival at the testing laboratory, samples were air dried and thereafter broken up for sieving. This was carried out in the usual way through 3", 1½", ¾", ⅜" sieves in the first instance, and thereafter through Tyler No. 3, 4 and 8 sieves. In order to save time, analysis by hydrometer followed. Fifty grams of that part of each sample which passed through the No. 8 sieve were taken and soaked in distilled water. This material was then used for the now standard method of hydrometer analysis.[2] Hydrometer readings were taken at intervals up to 2 hours from the time at which shaking of the mixture was stopped, and in this way grain sizes down to the equivalent of a diameter of

[2] See, for example Tentative method of mechanical analysis of soils. Proc. Am. Soc. Testing Materials 35: Pt. 1, p. 953, 1935.

about 0.005 mm, from an equivalent diameter of about 0.060 mm, were determined. The material was then carefully washed out onto a No. 200 sieve; that part which was retained was dried and

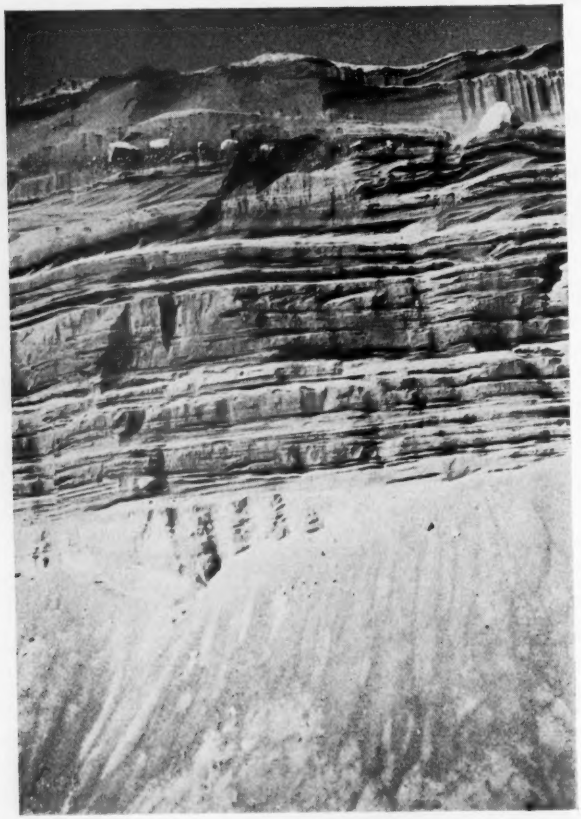


FIG. 3. Photograph of stratified sand and gravel.

analyzed by being sieved through No. 14, 28, 48 and 100 sieves. The results of this analysis were then plotted on a standard form of semi-logarithmic paper, one form being used for each test pit.

Of the 70 pits studied, 18 revealed sand and gravel as the predominant materials in the soil profile. Of these 18, 9 were adjacent to the dam site, and were clearly in alluvial material. The remaining 9 were located in higher ground, and from the stratified appearance of the sand and gravel in them, it is reasonably certain that they disclosed water-sorted glacial material. One of these pits (R) disclosed such excellent sand that the area around it was later stripped of overburden, and developed as the source of supply of fine sand used to improve the pit-run gravel concrete aggregate. An accompanying photograph (Fig. 3) shows the stratification. Some of the gravel thus revealed was used in the pervious section of the dam structure.

From all the test pits, 225 individual samples were obtained. Towards the end of the soil testing work, after it had been found that, in general, individual samples from the same test pit gave very similar analyses, it was decided to combine the several samples obtained from each pit and to prepare from the resulting mixture a "composite pit sample." Due account was taken of all noticeable variations in the soil profiles by weighting the respective amounts of the individual samples, when necessary. The object of this operation was to save time, in view of the pending start of construction, and this it did by reducing the number of samples to be analyzed to 139.

Of these 139 samples, 41 consisted of sand and/or gravel from the 18 pits already mentioned. The remaining 98 samples were all of material that was classed in the field as either "sandy clay" or "silty clay," being typical of the hard soil mixture that is generally known as "boulder clay." The uniformity of this material is shown by Fig. 4 for the analysis curves given by 79 of the 98 samples (44 individual samples and 35 composite pit samples) come within the limits shown on the chart. The chart shows, in addition to the two limiting curves, a number of typical analysis records.

There has been included also a graphical record of the average mechanical analysis of till or boulder clay from the Boston, Mass., district given by Prof. W. O. Crosby in one of the first, if not the

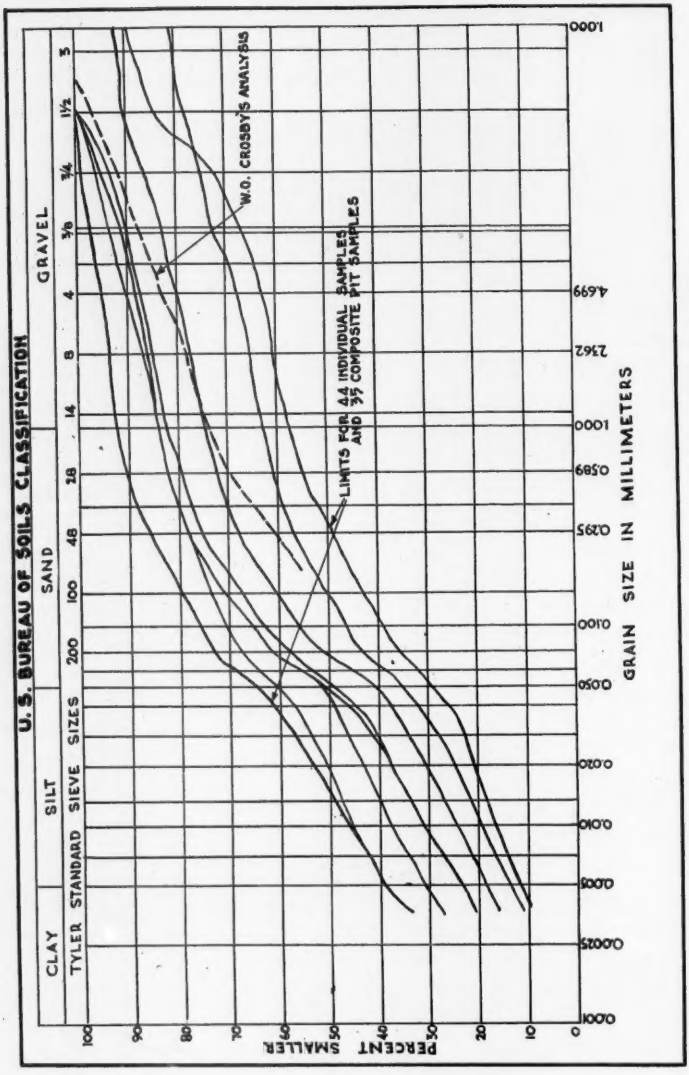


FIGURE 4: MECHANICAL ANALYSIS RECORD CURVES

first paper in English upon the composition of glacial drift.[3] It is interesting to note the close agreement of the two sets of analyses.

The uniform shape of the analysis record curves is also worthy of note. All those shown are slightly concave downwards. Of the analysis curves not shown (132 in number) only 17 did not conform generally to this shape. These exceptions were all from the pits that were excavated in sand and gravel; they displayed the usual steeply graded analysis curve in the sand range of particle sizes. This downward concavity is a marked feature of practically all other analysis record curves for glacial drift which the writer has examined; typical are the diagrams reproduced in Professor W. C. Krumbein's study of glacial till from the southern end of Lake Michigan.[4] It has been suggested that the shape of the curves shown in Fig. 4 is typical for residual soils and that if the concavity is reversed, a better graded soil mixture is denoted, typical of water-sorted soil mixtures.[5] The coincidence of analysis curves for glacial materials with the type curve for residual soils is a fact of some interest.

PHYSICAL CHARACTERISTICS.

Specific Gravity of Soil Solids. Concurrently with the prosecution of mechanical analyses, typical soil samples were selected and the specific gravity of the soil particles was determined by means of a Le Chatelier flask, using a 50-gram sample. Air was exhausted from the soil and distilled water, the vacuum obtained approximating to 29 inches of mercury. Values so determined for the specific gravity varied only between 2.77 and 2.78. So uniform were the results obtained that after eleven typical samples had been treated in this way, from pits well distributed over the area being studied, testing of this soil property was discontinued.

[3] Crosby, W. O.: Composition of the till or boulder-clay. Proc. Boston Soc. Nat. Hist. 25: 115–140, 1892.

[4] Krumbein, W. C.: Textural and lithological variations in glacial till. Jour. Geol. XLI: 382–408, 1933.

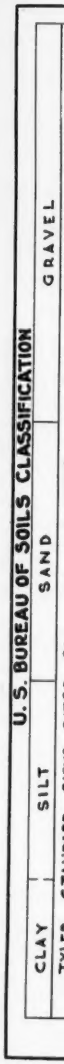
[5] See, for example Lee, C. H.: Selection of materials for rolled-fill earth dams. Proc. Am. Soc. Civil Engin. 103: 1–61, 1938 (and accompanying discussion).

Compaction and Optimum Moisture Tests. The work of Kelso in Australia,[6] and Proctor in the United States,[7] has demonstrated the importance, in earth dam construction, of the degree of compaction to which the soil is subjected and the moisture content of the soil when it is compacted. It is found that, when compacted under identical conditions, a soil mixture will steadily increase in weight as the moisture content increases until a certain maximum, or optimum, point is reached. If the moisture content is increased still further, the weight of the soil will decrease. The change in weight is explained by the action of the added water which first fills the voids between solid soil particles, displacing air as it does so, during which process the weight of the soil will obviously increase. Once all the voids are filled with water, the addition of more water serves to separate the soil particles, the additional water acting as a lubricant, and the weight decreases. A little consideration will show that in an earth dam, part of which will be saturated with water, it is desirable that the earth, when tamped in position in the dam, shall have a moisture content as close as possible to this optimum value so that, as water percolates through the dam, the volume of the saturated soil shall not change.

For the determination of this optimum moisture content in the laboratory, a technique has been developed by R. R. Proctor.[7] Sixteen typical composite pit samples from the Shand Dam site were selected and subjected to this testing procedure. Analysis record curves for the sixteen samples are given in Fig. 5, and it will be seen that they include two that do not conform closely to the general type, those for samples O and U. These soils were all tested by the Proctor method, which consists essentially in compacting a portion of the soil mixed up with a known percentage of water in a cylinder of known volume by means of which the unit weight of the compacted soil can be determined; compaction is standardized by the use of a ram of known size and weight

[6] Kelso, A. E.: The construction of the Silvan dam, Melbourne water-supply. Min. Proc. Inst. Civil Engin. 239: 403–446, London, 1936.

[7] Proctor, R. R.: Fundamental principles of soil compaction. Engin. News Rec. 111: 245, 286, 348, 372, 1933.



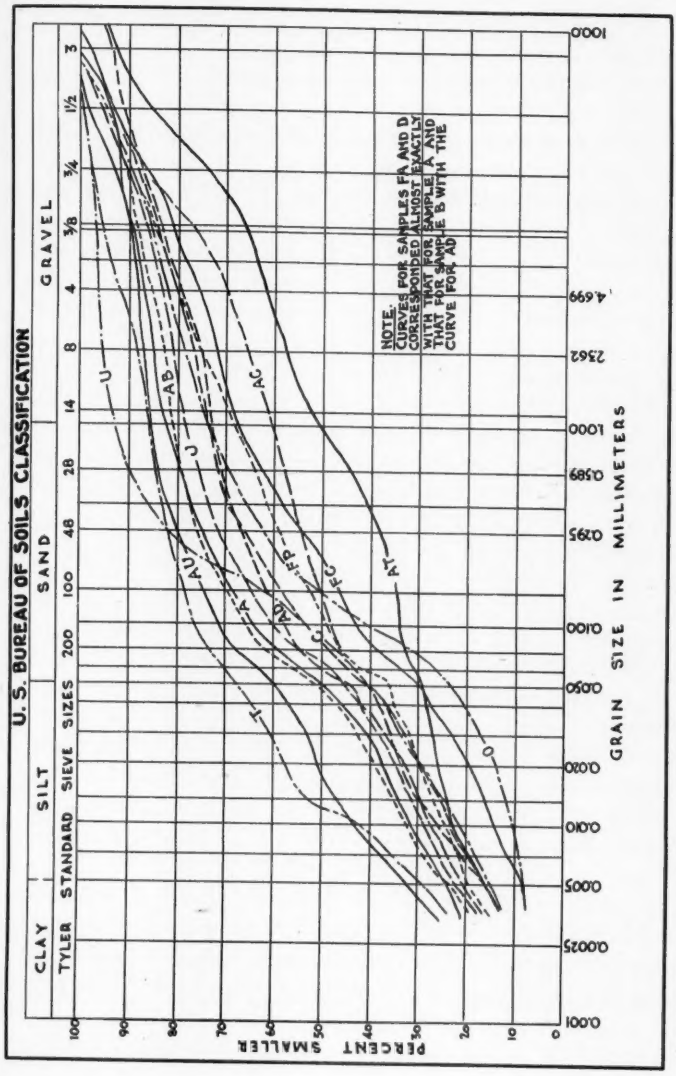


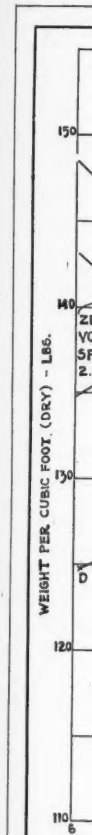
FIGURE 5: ANALYSIS RECORD CURVES FOR SIXTEEN SPECIAL TEST SAMPLES

(5½ pounds) dropped 25 times on to the sample placed in three successive layers, from a height of 18 inches.

The resulting compaction curves are shown in Fig. 6. The varying shape of these curves may be explained by the uneven distribution of observed results, but it will be seen that they all show clearly a maximum value for the soil moisture content. In addition, the right hand sections of all the curves come relatively close to, and are roughly parallel to the line marked "Zero Void Line." This line shows the theoretical weight of a material having a specific gravity of 2.75 having no intergranular voids other than those represented by the appropriate percentage of water present. The gap between the record curves obtained for the Shand samples and this line is accounted for by the fact that under the conditions of the Proctor test, which represent field conditions on a small scale, it is impossible to remove all the air from the voids in the soil, the gap thus representing the percentage of air still retained in the soil at the conclusion of the test.

Percolation of Water Through Soils. Another important soil property, in relation to the design of an earth dam, is the rate at which water will percolate through the soil of which the dam is to be made. This characteristic of the Shand soil samples was determined by testing specimens three inches thick, contained in an 8-inch diameter cylinder, and compressed between porous plates each one inch thick by a load equivalent to about 20 feet of soil. The test conditions were therefore equivalent to an average position of the soil in the dam structure. The test load was maintained by means of a heavy spring device, which enabled the test cylinder to be moved about in the laboratory. By means of sensitive micrometers the amount by which the soil samples were compressed by the test load was determined in each case.

In order to maintain uniform conditions of test, all soil samples were tamped in place, by a uniform number of equal blows from a standard rammer, after having been mixed up with the respective optimum moisture content. After compression of a sample had stopped, the test cylinder was connected to a column of water by a suitable connection which led the water to the bot-



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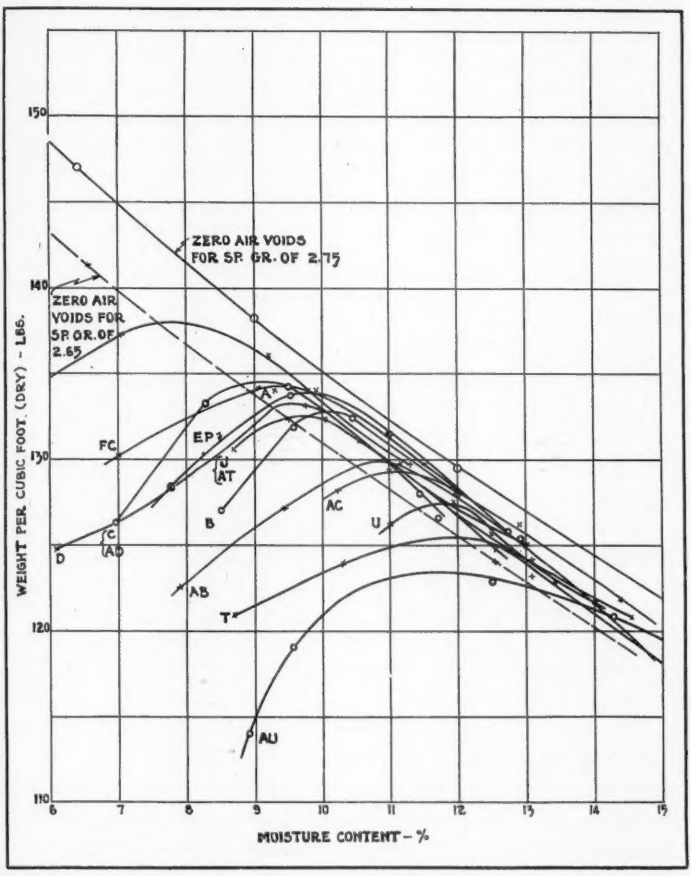


FIGURE 6: COMPACTION CURVES FOR 16 SPECIAL SAMPLES

tom of the soil sample, through which it percolated upwards, thus driving out entrapped air. When steady flow had been attained, readings were taken at the top of the water column to determine

the rate of flow. This rate was surprisingly low; most of the samples required a head of water of 40 feet before water would even pass through them within a reasonable period. Table I gives a summary of the results, and from this may be seen the uniformly low percolation rate. To facilitate interpretation of the rates given, it may be noted that the lower rates of flow correspond to a few cubic inches of water passing through the 3-inch sample, under a head of 40 feet, in 24 hours. Naturally, these

TABLE I.

PERCOLATION COEFFICIENTS AND CONSOLIDATION OF SOIL SAMPLES IN PERCOLATION TEST CYLINDERS.

Sample	Total Consolidation of 3-inch Sample (inches)	Consolidating Load (lbs/sq. inch)	Percolation Rate (cu. ft/sq. ft/year at unit gradient)
A	0.0951	20	0.074
C	0.0959	Do.	0.0319
D	0.0779	Do.	0.0156
J	0.1068	Do.	0.1060
O	0.0468	Do.	0.234
T	0.0897	Do.	0.052
U	0.0839	Do.	0.024
AB	0.0843	Do.	0.0196
AC	Not obtained		
AD	0.0740	Do.	0.0124
AT	0.1093	Do.	0.018
AU	0.0857	Do.	0.091
CH	0.0909	Do.	0.0161
FA	0.0953	Do.	0.0089
FC	0.0574	Do.	0.224
FP	Not obtained		

results were very satisfactory when considered in relation to the design of the Shand Dam.

Soil Shear Tests. The concluding series of tests, carried out on sixteen selected samples, consisted of determinations of the shearing strength of the soil. If thought is given to the structural action of the material of which an earth dam is made, it is clear that tensile stresses will not be of any significance since the material of which the dam is built possesses negligible tensile strength. Compressive stresses will not be of a high order. Shear stresses, however, may be relatively high and consequently govern the design. The purpose of the laboratory tests was to

determine the shearing strength of the soil samples, with varying moisture contents, so that the design calculations for the cross-section of the dam might be based on actual rather than on assumed soil shear strengths.

The tests were carried out in a shear testing machine, constructed at the University of Toronto. The shear box, in which the sample is placed, consists of two similar rectangular brass frames, enclosing an area of 240 square centimeters, and each about 4 cm high. When one is placed vertically over the other, they form the box into which the sample is placed. Serrated brass plates, fitting snugly into the box, grip the top and bottom of the soil sample, and a heavy brass plate of the same size forms a movable top. A constant vertical load can be applied to this top plate, through a spherical seat, and so any desired normal load can be applied to the soil sample. After this load is applied, the top section of the shear box can be separated slightly from the bottom section, by means of lifting screws, and secured in this position, the only connection between top and bottom sections being then provided by the soil sample which has been so placed in the box that this division of the box occurs along its longitudinal center plane. By means of a jacking device, the bottom of the box is then slowly pulled away from the top of the box, in a horizontal direction, and the resulting shear resistance developed by the soil is measured by a suitable load-measuring device. Movements of the box during test are measured by means of sensitive micrometer dials.

Figure 7 presents the results of a typical test in graphical form. It will be seen that as the horizontal deformation increases, the shear resistance also increases but at a gradually decreasing rate, finally becoming constant. The relation between these maximum values of shear resistance and the corresponding normal loads on the samples is shown in Fig. 8. From this it will be seen that a straight-line relationship exists. The angle of inclination of the line with the horizontal is known as the angle of internal friction, and the intercept with the vertical axis gives the value of the apparent "cohesion" of the soil particles. These two factors deter-

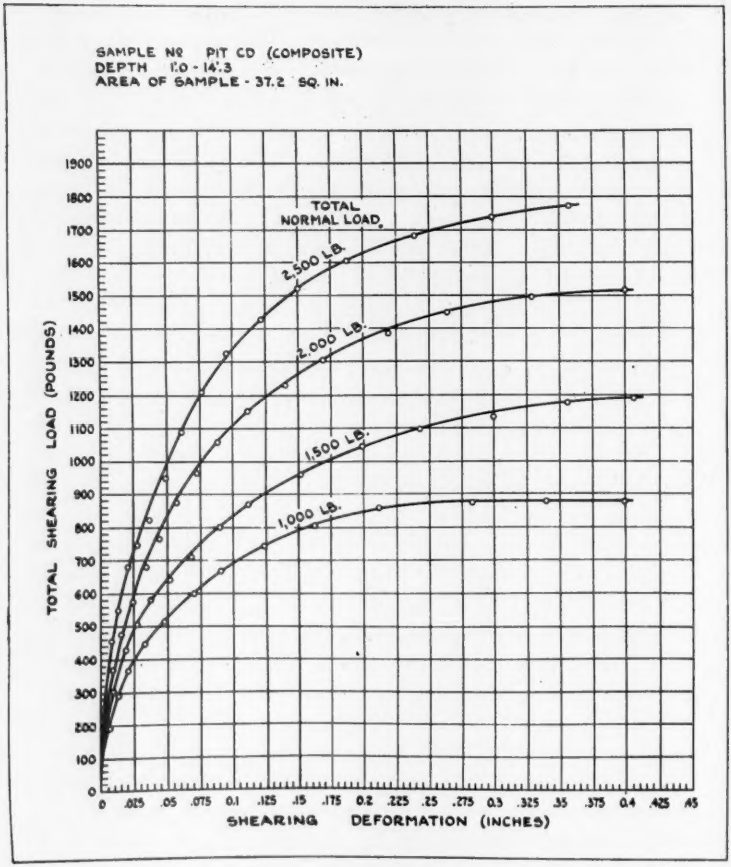


FIG. 7. RESULTS OF A TYPICAL SHEAR TEST.

mine the shear strength as required for design purposes. Fig. 8 is typical of the results obtained for all sixteen samples.

Since the soil was to be placed in the dam mixed with its optimum moisture content, tests were first conducted on samples

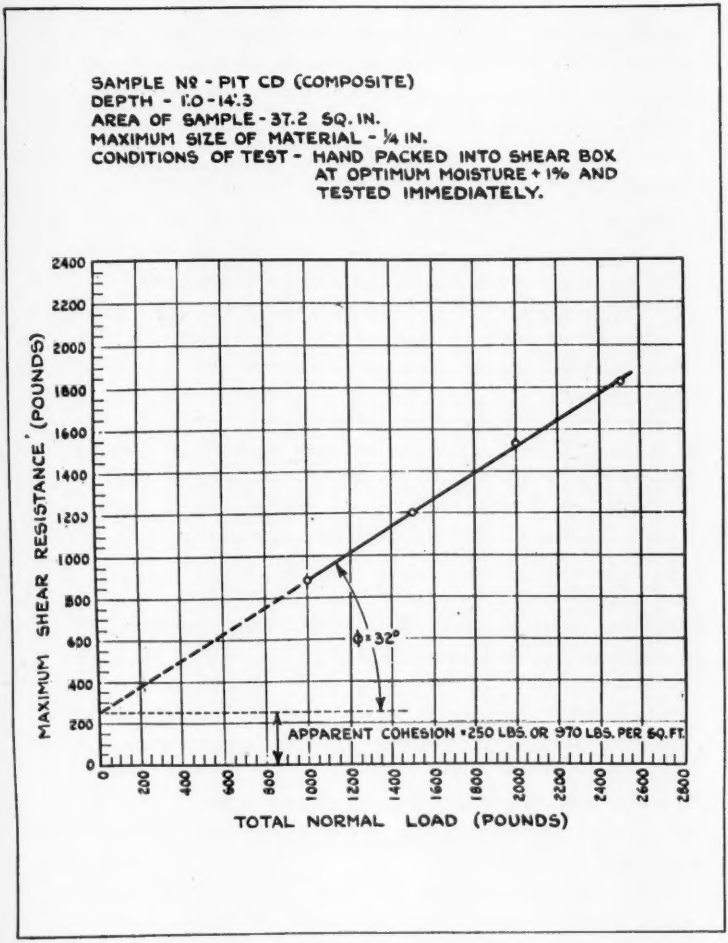


FIG. 8. TYPICAL RELATION BETWEEN NORMAL AND SHEAR LOADS.

of soil mixed up with the requisite amounts of water, and tamped into place in the shear box to approximately the same degree of compaction used for the Proctor compaction tests. In order to investigate the effect of variations in the quantity of water present upon the test results, an extensive series of tests was conducted upon sample AB, under the conditions already described (1) and also as follows:

(2) Soil at optimum moisture content plus one per cent, compacted in the shear box, and left under full normal load for a period of 12 hours or more before being tested;

(3) Soil mixed up with water in the shear box to the consistency of fluid mud, left under the full normal load for 12 hours or more, and then tested.

The second condition was investigated to take into account probable variations in the soil moisture contents obtained under field conditions. The third condition was analagous to the state in which the soil might be held to be when the dam is in use, and water has permeated through the lower part of the "impervious" part of its cross section. It was possible to carry out the test under the conditions described by having the shear box surrounded by a water bath, the water in which completely covered the sample, to which it had access through holes in the bottom of the shear box and through the porous plates which were substituted for the serrated plates used in the "dry" tests. Submerged tests were conducted on many samples other than AB, and in every case the soil sample removed from the box after the test was in the form of a solid state of compact soil even though at the start of the test the mixture was so fluid that it could have been "poured" into place from a container.

It was found that, within the limits of experimental error and allowing for the possible variations in the individual samples used, there was no appreciable difference between the results obtained under the three sets of conditions. This agreement was naturally welcome in relation to design work. It enabled all further shear tests to be carried out on samples in the first condition only.

REVIEW OF MECHANICAL TEST RESULTS.

The foregoing account describes briefly the testing procedure that was followed in connection with the soil investigations for the Shand Dam. In view of the urgency with which results were required, it was not possible to review carefully the results obtained until some time after the conclusion of the regular testing program. Three aspects of the results seemed to call for attention and are discussed below.

Uniformity of Mechanical Analyses. When comparing the mechanical analysis record curves, the general uniformity of the shape of all the curves obtained for soils other than those which were clearly predominantly sandy attracted attention. This feature is demonstrated, to some extent, by the group of typical curves shown in Fig. 4. Consideration was therefore given to other ways of plotting these analysis results in the hope that this uniformity might be better displayed, and so be more useful.

The most satisfactory arrangement was found to be given by plotting the proportions of the sand, gravel and clay sized particles on a tri-linear chart. Fig. 9 shows the appearance of the completed chart. The percentages shown have been calculated by considering all material in each sample below one millimeter in effective diameter as 100 per cent, and then subdividing this into sand (0.050 mm to 1.00 mm), silt (0.005 mm to 0.050 mm) and clay (below 0.005 mm) sized particles.

The chart shows clearly a definite "grouping" of points, apart from those denoting the sandy soils that were analyzed. Fifty-three per cent of the points representing clayey samples are located within the inner triangular limit marked on the chart, and 87 per cent within the outer limit indicated. Since variation in the quantity of particles larger than 1.00 mm in effective diameter, the gravel content of the glacial clay, does not affect the mechanical properties of the soil mixture (provided, of course, that the total quantity of gravel remains the minor constituent) it would appear that the use of this tri-linear "guide-chart" may prove to be a useful aid in the interpretation of the results of the mechanical analysis of glacial clays considered for use in engi-

neering work. Mechanical analysis can never be more than a general guide in the selection of soils for engineering purposes, and so the saving of time which can be effected by the use of such a chart as Fig. 9, as compared with plotting the full semi-logarithmic analysis record curve, would seem to be of some importance.

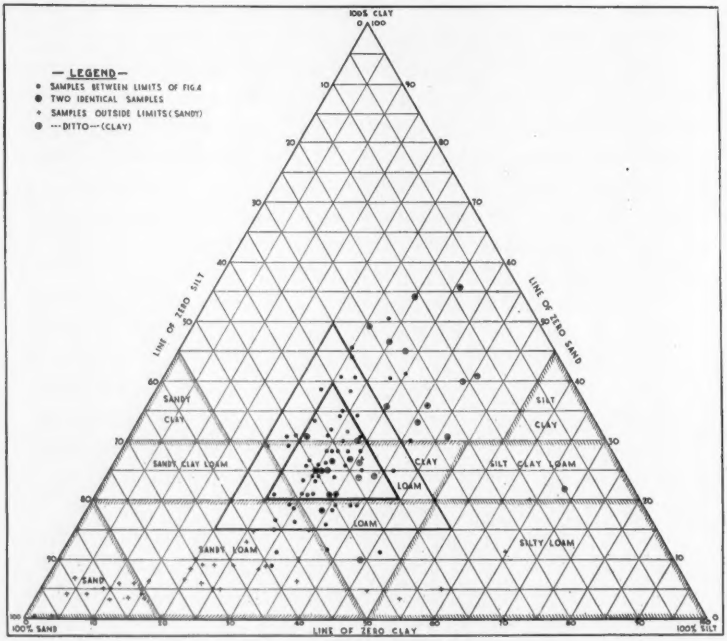


FIG. 9. Tri-linear chart showing mechanical analysis results.

Attempted Correlation of Test Results. During the conduct of the tests it was noticed that one or two samples (O and FC, for example) usually occupied a position in the summarized test results adjacent to one end of the list adopted. The attempt was therefore made to see if any general correlation existed between the various sets of test results for the complete series of samples.

Fig. 10 is a typical result of this enquiry. From an examination of this chart it can be said that, in general, no such correlation appears to exist.

Nature of Clay-sized Soil Particles. The fact that the soils being tested were known to be of glacial origin naturally suggested that the finest soil particles would be rock flour. It is interesting to note how the results of the mechanical tests would have led to this conclusion, irrespective of this prior knowledge.

The high specific gravity of the soil solids presented the first unusual feature. An average figure used as the specific gravity of soil particles is 2.65. This corresponds to the known specific gravities of the commoner type of clay-minerals (*e.g.* kaolinite 2.60). In view of the great accuracy required in carrying out specific gravity determinations, it might be thought that the value of 2.77 was unduly high because of experimental error. Reference to Fig. 6 shows that this uncertainty is unwarranted. It has already been pointed out that all the compaction curves approach closely the Zero Air Voids line, for a specific gravity of 2.75. As a matter of convenience, the Zero Air Voids line for a specific gravity of 2.65 has been added to the diagram, as a broken line. It will be seen to intersect all the compaction curves. This is an obvious physical impossibility, and so the specific gravity of approximately 2.77 is confirmed. This value suggests, if it does not prove the presence of some fresh minerals in the finest soil particles.

Final proof of this is afforded by the comparative shear tests made on sample AB and, indeed, by the shear test results generally. Fine grained clay soils develop their shearing strength primarily from their cohesive character, cohesion being an intramolecular attraction as yet imperfectly understood but known to be related to particle shape and size. It may be considered as a combination of "true cohesion" and "apparent cohesion," the latter being dependent upon capillary attraction developed by the small quantities of water that fill the voids between soil particles. Apparent cohesion is demonstrated by the fact that damp sand can be moulded, to a limited extent, whereas the same sand when

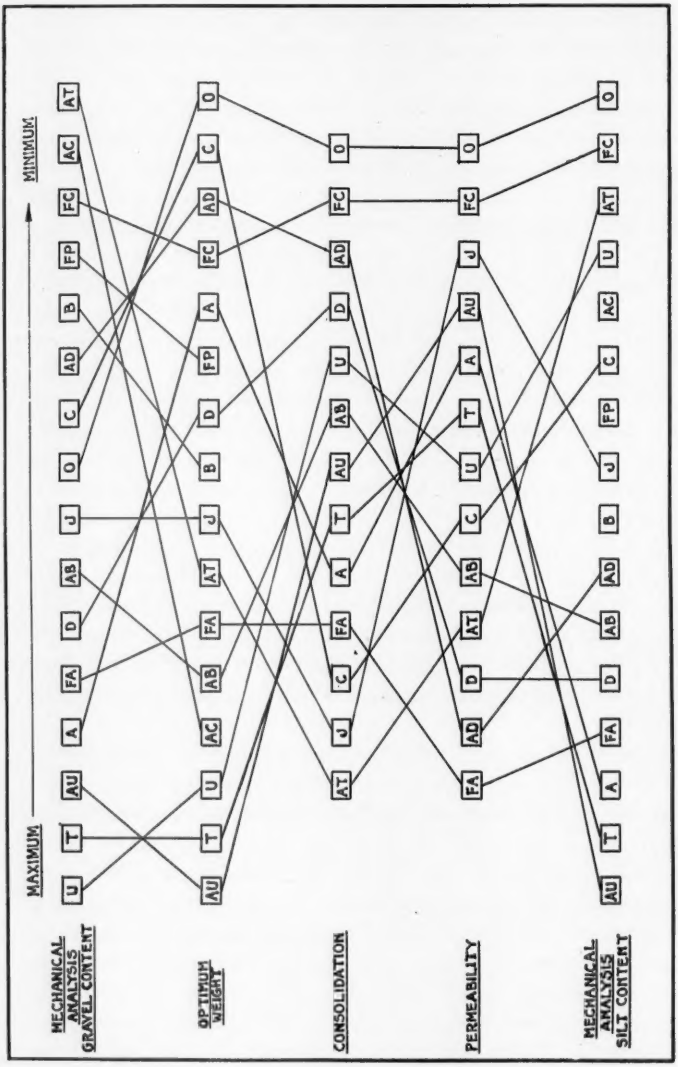


FIGURE 10: ATTEMPTED CORRELATION OF PHYSICAL TESTS

dried will not bind together at all. The other variable in the Coulomb expression for shear strength, the angle of internal friction, is known to be in the vicinity of 30° for granular materials such as sands and silts; its value for fine grained soils such as clays is not known with the same degree of certainty, but is generally understood to be lower, relatively, than for granular materials.

All the test results for the shearing strength of the Shand soil samples showed an angle of internal friction of 30° or more, and a low value for cohesion or more correctly apparent cohesion. Furthermore, the comparative tests on sample AB, as well as the other comparative tests on saturated soil and the same soil at optimum moisture content, gave practically identical shear strength irrespective of the initial moisture content of the soil. These results correspond with the behaviour to be expected from granular soils; they do not correspond with the results to be expected from soils containing an appreciable percentage of clay, as the "clay-sized particles" revealed by hydrometer analysis.

Considered together, these suggestions lead to the conclusion that these "clay-sized particles" correspond with the material properly known as clay in size only but are of such a nature that they behave as granular material. This they would do if they were finely ground fresh minerals, generally described as "rock flour" and produced by the mechanical action of glacial flow. Mineralogical examination might be utilized to corroborate this conclusion; it is hoped that this possibility can be studied at some future time.

CONCLUSION.

This paper is essentially a record of some of the mechanical properties of glacial drift from a location near Fergus, Ontario, which were determined during the course of an extensive program of soil testing carried out in connection with the construction of the Shand Dam of the Grand River Conservation Commission. It may therefore be described as a by-product of the

FIGURE 10: ATTEMPTED CORRELATION OF PHYSICAL TESTS

Commission's work, and appreciation of the action of the Commission in allowing this paper to be published is here recorded.

The work was carried out to the instructions of H. G. Acres and Co. Ltd., consulting engineers to the Commission, and thanks are due to Dr. H. G. Acres and Mr. A. W. F. McQueen, Hydraulic Engineer, for their agreement with publication of these soil test results and their interest in the aspects of the soil testing herein described.

Department of Civil Engineering,
University of Toronto,
September 28, 1942.

THE PARAGENESIS OF SOME GOLD AND COPPER ORES OF SOUTHWESTERN OREGON.[1]

WAYNE RUSSELL LOWELL.

ABSTRACT.

Copper ores in Southwestern Oregon are associated with greenstones and serpentines, while gold ores are associated with Tertiary lavas and nearly all of the pre-upper Cretaceous rocks. The ores consist of hypogene minerals deposited by mineralizing solutions ascending along fractures, faults and shear zones. The mineralizing solutions are believed to be related to quartz-diorite and related rocks. The ores represent deposition in the hypo-, meso- and epithermal zones. Generally deposition occurred in three stages separated by minor fracturing. Gold and copper minerals were deposited in the intermediate stage. Calcite and hydrous gangue minerals—chlorite, sericite and prehnite—were well developed along fractures in the sulphides during the late stage. Secondarily enriched ores are comparatively rare. Oxidation zones are commonly 25 to 30 feet deep rarely exceeding 100 feet. Unusual minerals identified included cassiterite, native bismuth, and tellurium.

INTRODUCTION.

THE mines included in this investigation are located in the area from Cottage Grove on the north to the Oregon-California boundary on the south between meridians 122° 30′ and 124° 00′. Those of the Bohemia district are situated in the Cascade Range about 35 miles by highway southeast of Cottage Grove, Oregon, and the remainder are located in the drainage basins of the South Umpqua, Rogue and Illinois rivers. Grants Pass, Oregon, is near the center of this area which has a radius of about 35 miles.

Ore specimens were collected from 34 mines (Fig. 1), selected on the basis of past production, accessibility of the workings, and present development. In so far as possible the specimens were collected from the veins, but in the case of inaccessible workings specimens were taken from the dumps.

[1] Part of a dissertation submitted to the faculty of the University of Chicago for the degree of Doctor of Philosophy, 1942.

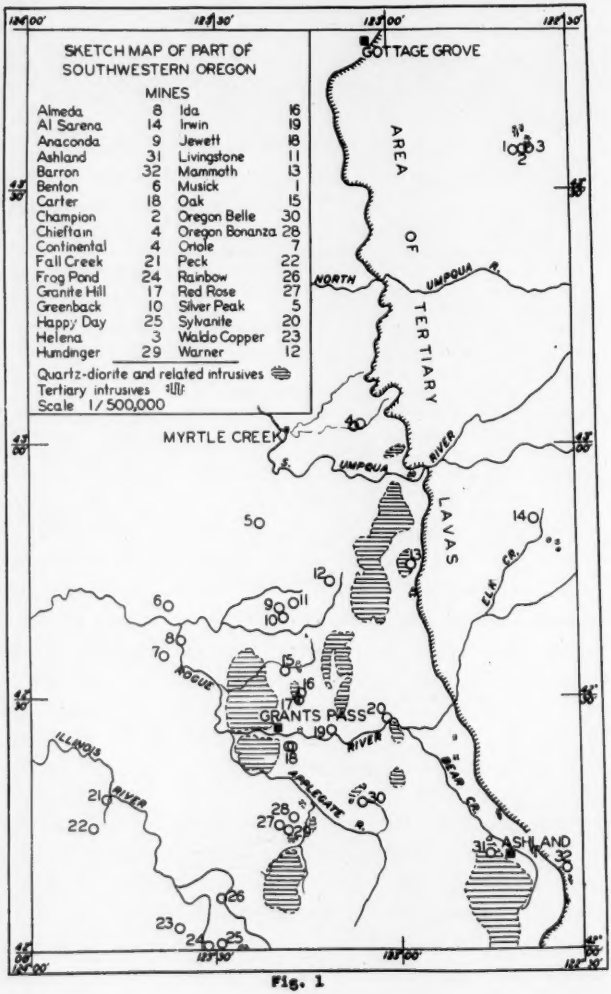

SKETCH MAP OF PART OF SOUTHWESTERN OREGON
MINES
Almeda 8
Al Sarena 14
Anaconda 9
Ashland 31
Barron 32
Benton 6
Carter 18
Champion 2
Chieftain 4
Continental 4
Fall Creek 21
Frog Pond 24
Granite Hill 17
Greenback 10
Happy Day 25
Helena 3
Humdinger 29
Ida 16
Irwin 19
Jewett 18
Livingstone 11
Mammoth 13
Musick 1
Oak 15
Oregon Belle 30
Oregon Bonanza 28
Oriole 7
Peck 22
Rainbow 26
Red Rose 27
Silver Peak 5
Sylvanite 20
Waldo Copper 23
Warner 12
Quartz-diorite and related intrusives
Tertiary intrusives
Scale 1/500,000
COTTAGE GROVE
AREA OF TERTIARY LAVAS
NORTH UMPQUA R.
MYRTLE CREEK
UMPQUA RIVER
ELK CR.
ROGUE
GRANTS PASS
ILLINOIS RIVER
APPLEGATE
BEAR CR.
ASHLAND
124°00'
123°30'
123°00'
122°30'
43°30'
43°00'
42°30'
42°00'

Fig. 1

Due to the widespread mineralization of southwestern Oregon several reports dealing with the geology, mineral resources and mines of this region have been published. The geology of five 30 minute quadrangles has been mapped; these include the Roseburg, Riddle, Butte Falls, Medford, and Grants Pass quadrangles. In addition, U. S. Geol. Surv. Bulletin 893 includes a reconnaissance geological map of the Cascade Range and a more detailed geologic map of the Bohemia district. These maps together with reports dealing with mineral resources and mine descriptions were prepared by the U. S. Geological Survey, by the Oregon State Department of Geology and Mineral Industries, or as co-operative projects by the two organizations.

This investigation was undertaken in the hope that a regional paragenesis study of ores from several mines of the area would yield data pertinent to the temperature and pressure conditions prevailing during the mineralization period and possibly information as to the effect of structural control on the circulation of the mineralizing solutions. The study was outlined, developed and completed under the direction of Dr. Edson S. Bastin. Dr. Norman L. Bowen gave frequent aid and advice in the petrographic work. The Oregon State Department of Geology and Mineral Industries contributed to the study by financing part of the field expenses and by furnishing unpublished data about the mines.

GEOLOGY.

Stratigraphy.

Paleozoic or Older Rocks. These rocks include the older schists and metavolcanics and metasediments, described by F. G. Wells,[2] for the Grants Pass and Medford quadrangles. The older schists occupy 40 or 50 square miles along the southern border of the area and lie partly in the southeastern corner of the Grants Pass and partly in the southwestern corner of the Medford quadrangles. Because of severe metamorphism they

[2] Wells, F. G.: Preliminary geologic map of the Grants Pass Quadrangle, Oregon. Oregon Dept. Geol. and Min. Indus., 1940. Preliminary geologic map of the Medford Quadrangle, Oregon. Oregon Dept. Geol. and Min. Indus., 1939.

are considered the oldest rocks of the region. The metavolcanics, enclosing lens-shaped beds of metasediments, make up a thick series of rocks which underlie a considerable part of the Grants Pass, Riddle and Medford quadrangles. The metavolcanics are pale green to greenish-gray with textures varying from fine to moderately coarse-grained. Much of the series consists of porphyritic rocks with plagioclase and former pyroxene phenocrysts in a microcrystalline matrix. The metasedimentary rocks include beds of argillite, chert, quartzite and limestone. The general strike is usually east of north with steep southeast dips. This Paleozoic series of rocks is apparently the southern extension of the greenstones and May Creek schist as mapped in the Riddle [3] and Butte Falls quadrangles.[4]

Jurassic Rocks. The Galice formation (L. Jurassic) outcrops mainly in the Riddle Quadrangle where it includes fine-grained, dark slate with some sandstone and conglomerate, and is mapped separately from the parallel bands of greenstone. Apparently equivalent rocks [5] in the Grants Pass Quadrangle are interbedded with and overlain by volcanic rocks that are nearly the same age as the sedimentaries and are considered to be Jurassic in age. The Dothan formation (U. Jurassic) occurs mainly in the Riddle Quadrangle; it consists chiefly of hard sandstone with some conglomerate and some gray shale. The Jurassic rocks have a general N. 30° E. strike and dip steeply to the southeast.

Cretaceous Rocks. The Cretaceous rocks of the mapped area are confined to the northern part of the Riddle and the southern part of the Roseburg quadrangles but probably extend into the unmapped area to the west. In the mapped area the Cretaceous rocks include the Myrtle, Chico, Horsetown and Knoxville formations consisting of shales, sandstones and conglomerates. The Chico formation also outcrops as a narrow band along the southwest side of Bear Creek Valley in the Medford Quadrangle where

[3] Diller, J. S., and Kay, G. F.: Geologic atlas of the United States, Riddle Folio, No. 218, Oregon. U. S. Geol. Surv., 1924.

[4] Wilkinson, W. D.: Reconnaissance geologic map of the Butte Falls Quadrangle, Oregon. Oregon Dept. Geol. and Min. Indus., 1941.

[5] Wells, F. G.: op. cit. (Grants Pass Quadrangle).

it unconformably overlies the older rocks and has a general northwest strike with dips varying up to 30° N.E.

Tertiary Rocks. The Umpqua formation (Eocene) outcrops as a northwest trending band on the northeast side of Bear Creek Valley in the Medford Quadrangle where it generally strikes northwest and dips northeast at a low angle beneath the Tertiary volcanics to the east. Farther north in the Butte Falls Quadrangle the strike is more eastwest with low southerly dips. In the Roseburg Quadrangle the Umpqua formation covers about one-third of the area. Here the average strike is northeast, although there is much variation and dips are both northwest and southeast.

Tertiary lava flows occupy approximately the eastern third of the region and extend from Cottage Grove on the north to Ashland on the south (Fig. 1). These flows belong to the western Cascade volcanic rocks and have been divided into two groups[6] on the basis of types of flows. One group consists of black lavas and volcanic breccias with minor rhyolite, andesite and tuff; the second group is dominantly andesitic lavas and volcanic breccias. The lavas, ranging in age from Eocene to middle Miocene, have a gentle east to northeast dip.

Intrusive Rocks. Intrusive rocks ranging in composition from peridotite, gabbro, diorite, quartz-diorite, granodiorite and granite outcrop in the region (Fig. 1). Generally the exposed portions of these rocks are comparatively small; however, a few bodies are many square miles in extent. Usually the more basic rocks have the smallest areal outcrops. The peridotite rocks have been more or less altered to serpentine. The ages of the intrusives vary from Mesozoic (late Jurassic?) to late Miocene. In the Roseburg Quadrangle gabbro intrudes the Myrtle formation (Cretaceous) and diabase cuts the Umpqua formation (Eocene);[7] in the Grants Pass Quadrangle the youngest intru-

[6] Callaghan, Eugene, and Buddington, A. F.: Metalliferous mineral deposits of the Cascade Range in Oregon. U. S. Geol. Surv. Bull. 893, Plate I, 1938.

[7] Diller, J. S.: Geologic atlas of the United States, Roseburg Folio, No. 49, Oregon. U. S. Geol. Surv., 1898.

sives are older than the Chico formation (Cretaceous);[8] while in the Medford[9] and Butte Falls[10] quadrangles the diorite sills and basalt dikes cut Tertiary lavas and are late Tertiary in age. Contact metamorphic aureoles have been developed in the intruded rocks.

In the Bohemia district small stocks and dikes of intrusive rocks,[11] ranging from granite and dacite porphyry to diorite, cut the Tertiary lavas with the development of contact metamorphic aureoles. The veins and small elongate stocks have a general parallel strike of west to northwest.

Structure.

The structures of the rocks of this region are very complex. Folding and faulting have been operative over a long period and the rocks older than the Chico formation (U. Cretaceous) have been strongly deformed.

The rock formations as mapped in the area are exposed on the surface as bands trending about N. 30° E. The strike of the formations closely follows this trend although locally strikes and dips vary considerably. Generally steep to vertical dips to the southeast prevail.

The oldest rocks of the region outcrop in the southeastern part of the area and the younger metamorphics occur to the northwest. Along the northwest edge of the Grants Pass Quadrangle, Jurassic rocks, striking northeasterly and dipping steeply to the southeast, appear to underlie the older metavolcanics, a relation that may be due either to overturning or overthrusting of the metavolcanics over the Jurassic rocks.

A major synclinal structure is indicated by the northwestward dip of the metavolcanics of the Medford Quadrangle and by the southeastward dip of these rocks in the Grants Pass Quadrangle.

[8] Wells, F. G.: op. cit. (Grants Pass Quadrangle).
[9] Wells, F. G.: op. cit. (Medford Quadrangle).
[10] Wilkinson: op. cit.
[11] Callaghan and Buddington: op. cit., p. 41.

Faults in the pre-Cretaceous rocks are numerous. Several fairly large faults are shown on the geologic maps of the area. Most of the mine workings reveal one or more faults.

THE ORE DEPOSITS.

Copper Deposits.

Distribution. Copper prospects and mines in the area are not localized. In the past several districts have been prospected and studied, and prospects and mines have been developed in each. Of these districts the Takilma-Waldo and Silver Peak areas are important. The Almeda mine is reported to have been a copper producer and to have considerable copper ore reserves. Some development work has been done in the area south of Drew, Oregon, at the Banfield and Mammoth Lodge claims. One of the earliest areas prospected for copper was the Rancherie and Fall Creek area west of Selma, Oregon, on the Illinois River.

Relation to Country Rock. The copper deposits occur in metamorphic rocks. Various descriptions stress the association of copper with greenstones and with serpentine which is abundant in the region and has been derived by alteration of ultra-basic intrusive rocks of peridotitic and pyroxenitic types. Serpentinized rocks have been intruded into all the pre-Cretaceous rocks and are probably younger than most of the greenstones with which they are in contact.[12] Of the five copper mines and prospects visited, three are associated with greenstones and serpentine, one (Silver Peak mines) with greenstone and schist, and one (Mammoth Lode) with the May Creek schist.

Associated Intrusive Rocks. Intrusive rocks outcrop near two of the mines and are known to occur in the vicinity of two others; serpentinized rocks are closely associated with three of the mines. The Mammoth Lode and Oak mines are near quartz-diorite masses and quartz-diorite rocks are exposed a few miles distant from the Silver Peak mines and the Waldo Copper mine.

Structural Relations. Faulting or shearing has been operative at five copper mines and prospects. Evidence of post-min-

[12] Wells: op. cit. (Grants Pass Quadrangle).

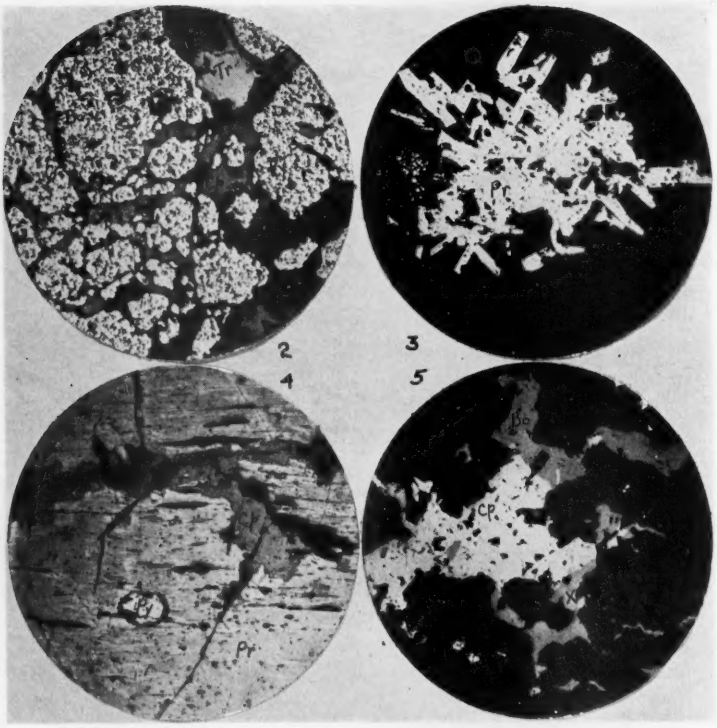


FIG. 2. Sphalerite (Sph)-Bornite (BO)-Galena (G)-Chalcopyrite (Cp) segmented veinlets in pyrite (Py). Tetrahedrite (Tr). Barite (Ba) replaces quartz (Q). (Silver Peak mines.) Magnification 48 ×.

FIG. 3. Pyrrhotite (Pr) automorphically replacing quartz (Q). (Waldo Copper mine.) Magnification 48 ×.

FIG. 4. Pyrite (Py) replacement of pyrrhotite (Pr) develops rounded grain. Chalcopyrite (Cp) replaces pyrrhotite along a fracture (Fall Creek Copper mine.) Magnification 48 ×.

FIG. 5. Bornite (Bo) and chalcopyrite (Cp) reversible relationships. (×) is an area of bornite-chalcopyrite intergrowth similar to exsolution textures obtained by Schwartz in the laboratory. Matrix is quartz. (Silver Peak mines.) Magnification 48 ×.

eral movements is abundant, but pre-mineral faulting or shearing is not so obvious, although it can be inferred from polished specimens which show, for nearly all the ores, that fracturing followed deposition of the earliest as well as the later formed minerals, usually with later minerals filling the fractures. The evidence implies a lack of static conditions during and following mineralization, and it seems reasonable to infer that stresses had already resulted in zones of weakness if not of faulting prior to mineralization.

The ores at the Waldo Copper mine and the Fall Creek prospect are closely associated with greenstone-serpentine contacts but in each case the ore is in serpentine. It is not known whether these are fault or intrusive contacts. Some post-ore movement has occurred at both of these mines as the ores are slickensided. The ore replaces the country rock parallel to the schistosity at the Silver Peak mines and the Oak mine. A fault parallels the mineralized zone at the Oak mine and is probably pre-ore. Pre-mineralization faulting has not been reported at the Silver Peak mines; however, post-mineral faults parallel and cut the ore zone.

The Orebodies. The copper ore is in tabular and irregular lens-shaped bodies which range from very small to large masses. The orebodies in serpentine (Waldo Copper mine and Fall Creek prospect) are generally small to moderate discontinuous lenticular bodies. The original size and continuity may have been considerably altered by faulting as Winchell [18] indicated has happened at the Waldo Copper mine. The ore, in greenstones and schists, occurs in shoots parallel to the schistosity.

Nearly all of the orebodies show more or less gradational contacts. These are most prominent in the schist and greenstone deposits of the Silver Peak, Oak and Mammoth Lode properties. In ore enclosed by serpentine, the contacts are quite sharp, especially where post-ore movements have taken place, although polished specimens show textures indicating replacement of ser-

[18] Winchell, A. N.: Petrology and mineral resources of Jackson and Josephine counties, Oregon. Mineral Resources of Oregon, 1: 253, 1914.

pentine minerals by sulphides as well as sulphide veinlets cutting the serpentine.

Gold Deposits.

Distribution. There are numerous gold mines and prospects scattered throughout southwestern Oregon in the area extending from the Pacific Coast to the Cascade Range on the east. The sites of the largest and most successful mines are located in the Grants Pass area.

Relation to Country Rocks. Gold-bearing quartz veins are widely distributed in this area and are found in all of the pre-upper Cretaceous rocks. Greenstones are chiefly mentioned as the host rocks in much of the literature dealing with the mines. Some productive veins are associated with metamorphosed sediments, quartz-diorite, and granodiorite, and some are found in peridotites and related serpentines. A few widely scattered veins are located in the belt of Tertiary (Miocene) lavas overlying the eastern part of the area.

Associated Intrusive Rocks. Mineralized zones in the Tertiary lavas are closely associated with igneous rocks ranging from dioritic to granitic.[14] In the Bohemia district several of the mines are exploiting veins within the intrusive rocks. In the older rocks, many of the gold-quartz veins occur in an area where several small and a few large bodies of quartz-diorite and related rocks crop out at the surface. These igneous rocks are thought to be surface exposures of a large batholith underlying the region. Some mines and prospects are located on veins that are several miles from surface exposures of acid igneous rocks. Two mines, the old Granite Hill and the Ashland, are located within quartz-diorite and granodiorite respectively.

Structural Relations. Veins occur most frequently in faults or faulted zones which are found cutting all of the older rocks of the region and may or may not parallel the schistosity of metamorphic rocks. Some are located in or near contacts of intrusive and sedimentary rocks; some cut both metavolcanic

[14] Callaghan and Buddington: op. cit., p. 22.

rocks and metasediments or parallel their contacts; other veins in greenstone are reported to die out or to be cut off at serpentine contacts with the greenstone.[15]

In general the gold-quartz veins may have diverse orientations but in the Grants Pass Quadrangle Wells[16] finds that the majority strike either N. 60° W. or N. 30° E.; the dips range from vertical to 40° and they slope both to the northeast and southwest and to the northwest and southeast.

The Orebodies. The gold-bearing quartz occurs in veinlets, veins, and brecciated zones. The veins are not persistent for any distance and within their known extent pinch and swell. These irregularities result in lens-shaped and tabular bodies of quartz with greatest dimensions parallel to the fissure or fault zone. Each vein may contain one or several lenses ranging from a few feet to a few hundred feet in length and averaging three to four feet wide. Locally widths are much greater. A few veins occupy strong persistent fracture zones where they may have an en echelon arrangement. Only rarely is ore developed in rock adjacent to the veins.

Within the quartz veins, commercial ore is usually confined to shoots whose limits are determined by the grade of ore that can be profitably worked. The "shoots" are related to structural or textural features. Intersections of fractures, shears, or faults may result in development of higher-grade ore. At the Sylvanite mine[17] this type of structural control is reported to have resulted in the development of an ore shoot which was continuous down a fault intersection for 600 feet and discontinuous for another 200 feet. Ore shoots may develop along permeable zones in veins during the final stages of mineralization. This type may be much more irregular in regard to high-grade ore.

Sharp contacts are characteristic of the gold-quartz veins and the country rock. Some brecciated or sheared zones may show

[15] Diller, J. S.: Mineral resources of southwestern Oregon. U. S. Geol. Surv. Bull. 546, 1914.

[16] Wells: op. cit. (Grants Pass Quadrangle).

[17] Unpublished material from the office files of the State Assay Laboratory, Grants Pass, Oregon.

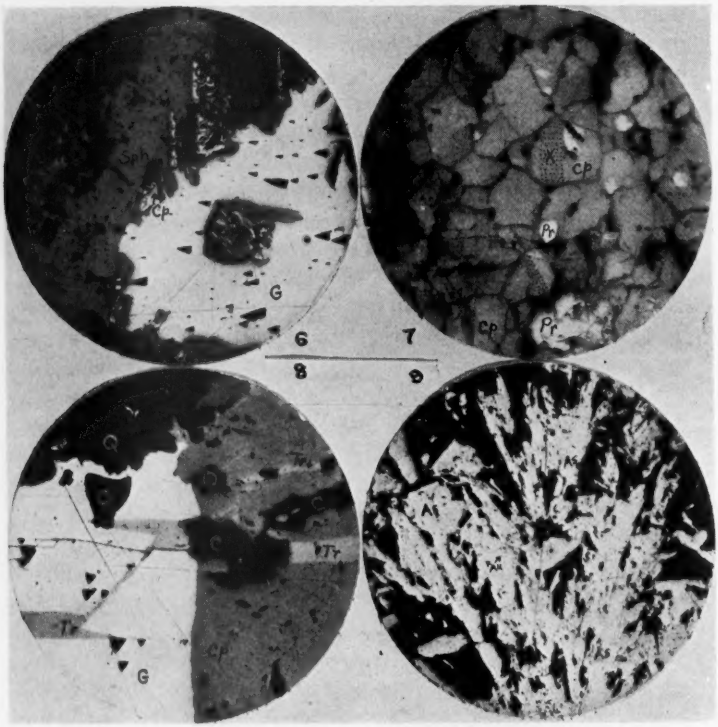


FIG. 6. Specularite (S) developed along sphalerite (Sph)-galena (G) contact. Chalcopyrite (Cp). (Musick mine, Bohemia district.) Magnification 48 ×.

FIG. 7. Chalcopyrite (Cp) and an unidentified mineral (×) in relations similar to those exhibited by chalcopyrite and cubanite. (Fall Creek Copper mine.) Magnification 48 ×.

FIG. 8. Tetrahedrite (Tr) veinlets cutting chalcopyrite (Cp) and galena (G). Quartz (Q); cavities (c). (Helena mine, Bohemia district.) Magnification 48 ×.

FIG. 9. Arsenopyrite (As) in frond-like growth. Gold (Au) blebs parallel the fronds. (Warner prospect.) Magnification 48 ×.

more or less gradational zones due to the amount of country rock enclosed in the veins. Gradational contacts are developed in at least two mines (Almeda and Anaconda) where the ore occurs in contacts between igneous rocks and slates. The ore has developed in the porphrytic-dacite (Almeda) and greenstone (Anaconda) by replacement, while the ore and slate contacts are comparatively sharp at both mines.

Mineralogy.

For the most part the gold ores of the area are similar in mineralogy. The sulphide minerals vary from mine to mine and one or more of the various minerals may be dominant so that an ore may be described as a pyrrhotite or an arsenopyrite-bearing ore. At the Peck and Anaconda mines, the ore is dominantly arsenopyrite and quartz. The Humdinger ore contains considerable pyrrhotite and some telluride. Tetradymite, native bismuth and cassiterite occur at the Irwin prospect; and tetradymite, native tellurium, and altaite occur at the Jewett mine. The ores are essentially pyrite and quartz, but generally sphalerite, chalcopyrite and galena are present in varying proportions with other sulphides or tellurides in minor amounts.

The copper deposits can be classified into two types of ore on the basis of the mineralogy. The first includes the Waldo and Fall Creek ores which are high in pyrrhotite with varying amounts of pyrite and chalcopyrite. The Fall Creek ore contains some pentlandite, while some arsenopyrite, sphalerite, and rarely native gold are present in the Waldo ore. In the second type, represented by the Silver Peak and Oak mines, pyrrhotite was not observed and sphalerite becomes nearly as abundant as chalcopyrite.

Chalcopyrite is the important primary copper mineral in both types of deposits. Tetrahedrite, tennantite and primary bornite are intergrown with chalcopyrite in the Silver Peak ores. Secondary copper sulphides, oxides and carbonates are not abundant.

The metallic minerals have been identified by various etch

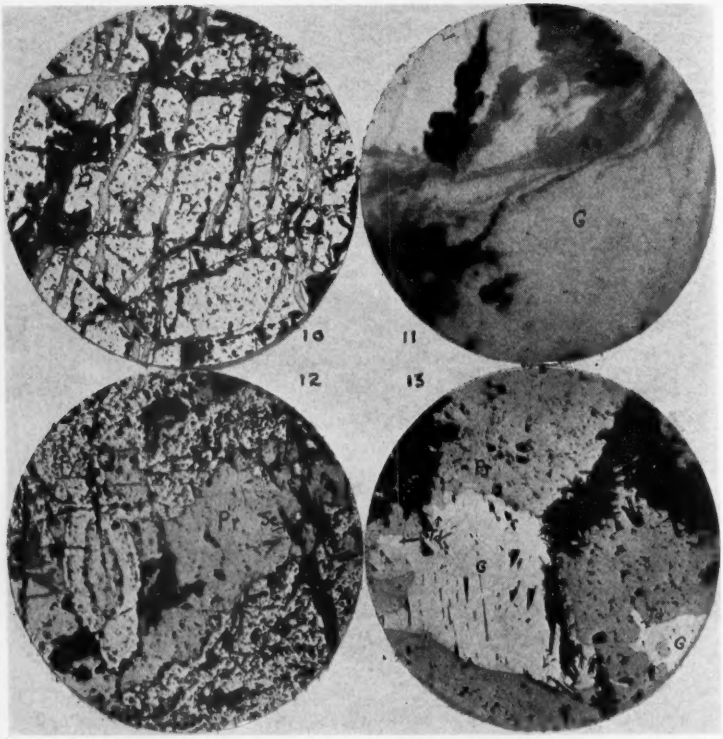


FIG. 10. Gold (Au)-quartz (Q) segmented veinlets in pyrite (Py). (Ashland mine.) Magnification 48 ×.

FIG. 11. "Steel" galena (G) and gold (Au) streamers. Galena reacted to deformation by granulation and recrystallization, and gold flowed. (Granite Hill mine.) Magnification 200 ×.

FIG. 12. Pyrite (Py) replacement of pyrrhotite (Pr); pyrite is definitely related to and later than sericite (Sc) veinlets. The ellipsoidal form may be marcasite although it grades into pyrite. (Humdinger mine.) Magnification 48 ×.

FIG. 13. Sericite veinlet cuts pyrrhotite (Pr) and galena (G). Tetradymite (Td) grains and rodlets along galena cleavage and boundary. (Humdinger mine.) Magnification 48 ×.

tests.[18] If etch tests and optical properties were not decisive, microchemical tests were made to determine the elements present.[19]

Hypogene Minerals. A small group of minerals—pyrite, quartz, sphalerite, chalcopyrite, galena and calcite—are present in varying amounts in practically all of the ores. The other minerals were identified in a few or only in one or two mines. Only the most interesting features of the mineralogy will be discussed.

Free gold was observed in many of the ores. In some ores it was in grains sufficiently large to see with the unaided eye, but generally it was very fine-grained and intimately intergrown with pyrite, arsenopyrite, quartz, galena, and chalcopyrite (Figs. 9, 10). An intimate and somewhat unusual intergrowth of gold, tetradymite, native tellurium, and altaite occurs in the Jewett and Carter ore (Fig. 14). An interesting reaction to deformation was revealed in gold ore from the Granite Hill mine. Pyrite shattered to tiny grains; chalcopyrite fractured on a much larger scale; galena, in part, fractured along cleavage lines and, in part, recrystallized to fine-grained steel-galena. Gold inclusions in galena were deformed by flowage to develop long wavy streamers (Fig. 11) as the galena reacted by granulation and recrystallization. The characteristic triangular pits of galena are absent in the area of gold streamers but are numerous in adjacent fractured areas.

Silver is present in small amounts in several ores but hessite was the only mineral identified. Some gold, at the Ashland mine, varies from a pale yellow to a deep yellow color and is probably silver-bearing. Tetrahedrite may be silver-bearing in some ores, although silver tests were negative.

Chalcopyrite is the dominant copper mineral with minor amounts of tetrahedrite and primary bornite. Chalcopyrite and bornite are frequently observed as intergrown areas of cross-hatch appearance (Fig. 5) in the Silver Peak ore. Bornite is al-

[18] Short, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 914, 1940.

[19] Short: op. cit.; Chamot, E. M., and Mason, C. W.: Handbook of Chemical Microscopy, 2nd edit. Vol. II. John Wiley, New York, 1940.

ways the matrix and chalcopyrite forms the bars which narrow at intersections. Contacts of bars with matrix are sharp. Nearby bornite-chalcopyrite contacts are also sharp and fail to show replacement phenomena.

Similar intergrowths have been reported as resulting from replacement of bornite by chalcopyrite, and by separation from a solid solution of bornite-chalcopyrite.[20] Schwartz believes that

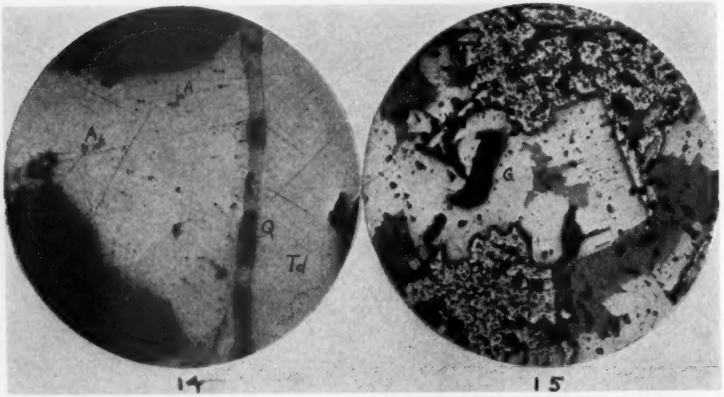


FIG. 14. Gold-quartz segmented veihlet cuts tetradymite (Td). Altaite (A) inclusions in tetradymite. (Jewett mine.) Magnification 48 ×.

FIG. 15. Sphalerite (Sph) and pyrite (Py) conform to galena (G). (Al Sarena mine.) Magnification 48 ×.

if the bars narrow at intersections they are most likely to be exsolution products, but if the intersections widen then replacement is indicated. He concludes that in the case of exsolution such intergrowths are formed at or above 475° C.

The chalcopyrite-bornite intergrowths of the Silver Peak ore are identical to similar intergrowths obtained artificially by Schwartz. The microphotographs show fractures cutting the intergrowths, but these are definitely later as the bars on one side

[20] Schwartz, G. M.: Intergrowths of bornite and chalcopyrite. ECON. GEOL., 26: 200, 1931.

are continuations of those on the opposite side. Covellite is slightly developed along the fractures. The evidence favors an exsolution origin for these intergrowths.

An unidentified mineral (X), is present in the Waldo and Fall Creek copper ores. Mineral X and chalcopyrite (Fig. 7) exhibit relations similar to those of cubanite and chalcopyrite. Such a mineral is reported by Schneiderhöhn and Ramdohr to occur with chalcopyrite in ores deposited at high temperatures.[21] They state that it is probably deposited in solid solution with chalcopyrite and "exsolution" results upon cooling. Laths of mineral X in chalcopyrite may be wide or narrow and often intersect to form V or triangle shapes. In the Fall Creek ore it may compose entire grains similar to those of Fig. 7.

Cassiterite is present at the Irwin molybdenite prospect. A spectrographic analysis shows Sn to be present in quantities between 0.1 and 1.0 per cent. Cassiterite is apparently somewhat replaced by chalcocite and covellite which makes its appearance deceiving. It occurs as small irregular and rounded grains in chalcopyrite and as cavity-fillings in pyrite.

Bismuth is also found in the molybdenite ore in quantities up to one per cent. The mineral assemblage is similar to that listed by Dana as occurring in association with cassiterite.[22] Alteration has affected both bismuth and tetradymite with development of a dark gray, nonmetallic mineral. Montanite, a secondary mineral containing Bi and Te, has been reported from Montana as encrustations on tetradymite, and this alteration product may possibly be montanite.

[21] Schneiderhöhn, Hans, and Ramdohr, Paul: Lehrbuch der Erzmikroskopie. Gebrüder Borntraeger, Berlin, 1931. Vol. II, pp. 349, 127–28. Mineral X is similar to a mineral which these writers report to be nickel-bearing; it shows no relief above chalcopyrite and is apparently of the same hardness. It is strongly anisotropic; polarization colors similar to those of pyrrhotite—gray and brown. The color in reflected light is yellowish-gray against pyrrhotite and light gray against chalcopyrite. This is probably the same mineral which Shenon describes as cubanite in the nearby Queen of Bronze and Cowboy mines in U. S. Geol. Surv. Bull. 846B, 1933.

[22] Dana, E. S.: A Textbook of Mineralogy, 4th edit. John Wiley, New York, 1932, p. 497.

Tellurides were identified in only a few of the gold-quartz ores. They seem to be most abundant in some of the ores from the Irwin prospect, Jewett, Carter, Red Rose and Humdinger mines. Although gold was observed to be closely associated with the tellurides from most of these mines, microchemical tests of the tellurides for gold and silver were negative while bismuth and lead tests were positive. The tellurides include native tellurium, tetradymite, altaite, sylvanite (?), and hessite (?).

Intimate intergrowths of native tellurium, tetradymite and altaite (Jewett mine) are common. In these instances all three minerals may be elongated with their cleavages parallel, and tetradymite and tellurium are recognized with difficulty. Etching with $FeCl_3$, however, produces an iridescent stain on tetradymite and the contacts then stand out. Altaite occurs in both of the other tellurides as rounded, irregularly rounded, lens-shaped areas, or combinations of these, within or along contacts.

Gold is intimately intergrown with tetradymite along twinning directions as microscopic grains and as elongated lens-like bodies parallel to tetradymite and tellurium cleavage.

Barite is fairly abundant at the Almeda and Silver Peak mines where in places it makes up much of the gangue. At the Helena mine, Bohemia district, barite in well developed crystals up to one-half inch long, lines vugs and fractures, and appears to be the latest mineral deposited. In the Almeda and Silver Peak ore, barite replaces quartz and fills fractures in pyrite, chalcopyrite, and tetrahedrite. The copper sulphides fill cavities in barite that are similar to cavity-fillings in quartz. Barite was deposited late in the mineralizing stage and was followed by sericite which is developed as shreds in fractures in barite. Some overlap with the copper sulphides and galena is indicated by unfractured areas where the sulphides appear to be cavity-fillings in barite and have sharp contacts with it.

Arsenopyrite is abundant in the Peck, Anaconda and Warner ores, and is present in minor amounts in a few others. It occurs as diamond-shaped sections, broken fragments and irregular masses.

Arsenopyrite from the Warner prospect is in spreading, fern-like forms of irregular rods, rectangular to parallelogram-shaped plates, and skeleton crystals (Fig. 9). Lines of tiny gold blebs parallel the fronds, and gold fills the cavities in the skeleton crystals. Some of these are several millimeters from the base to the ends of the fronds. The way gold blebs parallel the branches indicates the possibility of more or less continuity of spaces which permitted the gold-bearing solutions to circulate within and through the skeleton arsenopyrite crystals.

Late arsenopyrite is developed in sphalerite (Al Sarena mine), where it is related to fractures, and develops euhedral forms by automorphic replacement of sphalerite. The absence of similar veinlets in later sulphides indicates that this late arsenopyrite was deposited before chalcopyrite and galena.

Some pyrite, in the Bohemia and Barron ores, occurs as spherules in chalcopyrite. Spherules may be hollow or solid, and partially or completely filled by tetrahedrite, bornite and chalcopyrite. Similar occurrences of pyrite have been interpreted as resulting from deposition of pyrite as a gel followed by later dehydration and crystallization.[23] The absence of pyrite spherules in quartz, sphalerite, and galena, but their presence adjacent to these minerals suggests deposition in cavities between them. Later, chalcopyrite filled in the remaining space and partially replaced some areas. Numerous tiny pyrite blebs scattered through the chalcopyrite matrix appear to be replacement remnants. On the other hand, the presence of marcasite, as veinlets cutting sphalerite and galena, and rimming chalcopyrite, and as irregular anisotropic grains in spherulitic areas, suggests a close relationship between marcasite and pyrite spherules, but the spherules are not all anisotropic. Evidence places marcasite as one of the latest minerals, nearly as late as calcite, and although some pyrite seems to be intermixed, the chalcopyrite and tetrahedrite fillings of some cavities indicates that the spherulitic pyrite is earlier than these minerals.

[23] Schneiderhöhn and Ramdohr, op. cit., pp. 166–67.

In the Bohemia district the age relation of marcasite to specularite is not clear. Alteration products of pyrrhotite in the form of round grains (Fig. 4) in the Fall Creek ore, and ellipsoidal forms with concentric texture (Fig. 12) in the Humdinger ore, are similar to marcasite and pyrite textures described by Schneiderhöhn and Ramdohr and by C. P. Ross respectively. This mineral is intergrown with pyrite, and it may indeed be pyrite as it is not anisotropic and does not react to staining solutions. The absence of associated supergene sulphides in adjacent chalcopyrite suggests a hypogene origin.

Specular hematite is commonly observed in ores from the central part of the Bohemia area. In hand specimen it appears as deep red streaks following chalcopyrite-quartz contacts, and fractures, as alternating bands with quartz in ribbon veins, and as disseminated needles in quartz crystals. Under the microscope it forms slender needles and very rarely plates.

Hematite is later than sphalerite, chalcopyrite, and galena and earlier than carbonates. It automorphically replaces quartz, sphalerite, chalcopyrite and galena along contacts of these minerals (Fig. 6), and in one specimen was observed to cut sphalerite and an enclosed chalcopyrite veinlet.

Minor amounts of ilmenite are intergrown with specular hematite in the Bohemia ores.

Supergene Minerals. Secondary sulphides are not abundant and in many ores are absent. Oxidation and erosion appear to be about equally paced, therefore the oxidation zones rarely exceed a hundred feet in depth, and usually are much less. Limonite is the characteristic oxidation product. Gold values are reported somewhat higher than in unoxidized ore. The products of leaching are apparently carried away in the groundwater circulation as secondarily enriched ore, if present at all, is restricted to a narrow zone.

In the Bohemia veins chalcocite, bornite and covellite are developed as aureoles around adjacent minerals; bornite selectively replaces chalcopyrite, chalcocite replaces galena, and covellite replaces sphalerite. Cuprite was definitely identified only in the

Mammoth Lode ore where it selectively replaced chalcopyrite whereas adjacent sphalerite was replaced by covellite. In this instance no secondary copper sulphide appears to precede the cuprite as would be expected.

PARAGENESIS OF THE ORE MINERALS.

Paragenesis of the Gold Veins.

Pyrrhotite-gold-quartz Veins. The Humdinger and Frog Pond mines (Fig. 1) are located on veins of the pyrrhotite-gold-quartz type. The Humdinger ore is dominantly quartz with abundant pyrrhotite and pyrite and minor amounts of sphalerite, chalcopyrite and galena. Gold is present as native gold. The tellurides gave negative tests for gold, and a doubtful test for silver from a mineral identified by etch tests as hessite. In specimens studied from the Frog Pond mine, pyrrhotite was more abundant in wall-rock specimens adjacent to the vein and pyrite more abundant in the vein material. Other sulphides are sparse and minor differences exist in the sequence for each mine but the general features are similar.

The mineralization was apparently continuous, with the same order of deposition at each mine. The early sequence was pyrite, quartz and pyrrhotite with possible overlap of pyrite and quartz, and overlap of quartz and pyrrhotite.

A composite paragenesis sequence for the Humdinger and Frog Pond ores is shown below:

Pyrite cubes and fragments contain quartz and pyrrhotite veinlets. Angular pyrite fragments are so enclosed by quartz to indicate cavity-fillings, while quartz and pyrrhotite exhibit reversible relationships, and re-entrants of each in the other are common. Sphalerite was deposited next in the sequence. It occurs as cavity-fillings in quartz and pyrrhotite and is automorphic against chalcopyrite and galena.

Deposition of chalcopyrite and galena followed sphalerite. Galena displayed a tendency to wrap around some chalcopyrite indicating chalcopyrite in part was earlier. Late in this stage, gold, tetradymite, and hessite were deposited in the Humdinger ore. They frequently developed as irregular but rounded grains within chalcopyrite and galena or along chalcopyrite and galena contacts with pyrrhotite, and as cavity-fillings and in veinlets in all three sulphides and in quartz, and are contemporaneous with late chalcopyrite and galena.

Fracturing interrupted or ended this mineralizing epoch in both ores. At the Frog Pond mine, fracturing was followed by introduction of pyrite as veinlets in the older minerals. Sericite developed and filled fractures in the Humdinger ore (Fig. 13). Some chalcopyrite, galena, gold and tellurides are possibly later than some sericite as they fill triangular spaces between sericite plates although these triangular areas may be the result of automorphic replacement by sericite. Pyrite was introduced along both walls and within sericite veinlets in the form of parallel veinlets conforming to sericite plates on the one side and developing irregular contacts with pyrrhotite on the other. Extensive replacement of pyrrhotite by pyrite seems to have taken place in some areas. Reopening of sericite-filled fractures and opening of new ones apparently preceded the pyrite as pyrite veinlets also cut pyrrhotite, quartz, and the earlier sericite veinlets. Calcite-bearing solutions partially replaced sericite and pyrite veinlets along the central sericite band in the Humdinger ore, and developed veinlets in the Frog Pond ore.

Pyrrhotite, diagnostic of high temperature and pressure, is present in the early mineralization stage at each mine. The tel-

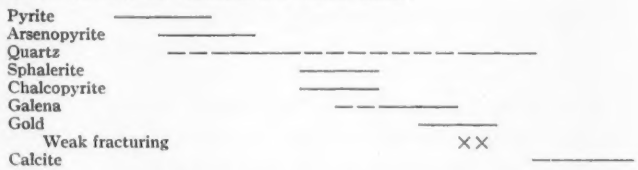
lurides, tetradymite and hessite deposited later occur in a wide range of temperature and pressure conditions. Diopside and adularia are diagnostic gangue minerals in the Humdinger ore; black tourmaline is reported in the Frog Pond ore. Diopside was observed as tiny grains enclosed by quartz, similar to that of the argillite wall rock, and separated from pyrrhotite masses by quartz. It seems to be developed along the vein wall-rock contact. Both diopside and tourmaline are diagnostic of high temperature-pressure conditions. Adularia appears as veinlets within the quartz vein and is a late mineral in, if not later than, the veins. Adularia is characteristic of the epithermal zone.[24]

The high temperature minerals—pyrrhotite, diopside, and black tourmaline indicate that the orebodies were deposited in the hypothermal zone.

Arsenopyrite-gold Veins. The arsenopyrite-gold veins have similar mineralogy to the other vein types but are characterized by abundance of arsenopyrite. Arsenopyrite-bearing ore is found at the Peck and Anaconda mines and the Warner prospect (Fig. 1), and consists mainly of quartz with arsenopyrite, although pyrite, sphalerite, chalcopyrite, and gold in minor amounts may be present. Gold is most abundantly associated with arsenopyrite but does occur in pyrite and quartz.

The general sequence of mineralization, as shown in the following composite paragenesis diagram, is typical for each of the mines in which variations are due to the absence of one or more minerals. For instance, in the Peck ore pyrite, chalcopyrite, and sphalerite were not observed.

Hypogene Minerals (Peck, Anaconda and Warner mines):



[24] Ore Deposits of the Western States. A. I. M. E., New York, 1933, p. 36.

Pyrite, arsenopyrite and then quartz, with some overlap, were the first minerals to be deposited. Pyrite, as cubes, is automorphic against arsenopyrite and quartz, with rarely a diamond-shaped section of arsenopyrite enclosed in a pyrite cube. Arsenopyrite is commonly automorphic against quartz, although many sections are only partially developed. Quartz veinlets, continuous with quartz matrix, cut pyrite and arsenopyrite. Evidence for quartz overlap with pyrite is not decisive.

Sphalerite and chalcopyrite were apparently deposited next and occur as cavity-fillings in quartz or between arsenopyrite-quartz contacts. Chalcopyrite cavity-fillings occasionally occur in arsenopyrite. Sphalerite and chalcopyrite were not observed together, but since they exhibit similar relations to the other minerals they appear to be contemporaneous.

Galena wraps around both sphalerite and chalcopyrite and is evidently younger. Gold fills cavities in arsenopyrite and as rounded to automorphic grains is enclosed by galena. Tiny gold veinlets cut arsenopyrite and galena. Gold and galena are contemporaneous with gold deposition continuing slightly beyond galena.

Fracturing followed galena and gold deposition with quartz introduced into the fractures. Some quartz veinlets in galena are continuous with quartz matrix and may indicate that quartz deposition was continuous from the early to the late mineralization period. Quartz deposition may have given way to calcite-bearing solutions.

Mineralization was continuous with the early minerals overlapping in the early stage. The intermediate stage, represented by sphalerite, chalcopyrite, galena and gold, was apparently ended by a period of minor adjustments within the veins. In the late stage quartz and calcite veinlets cut the sulphides and quartz gangue.

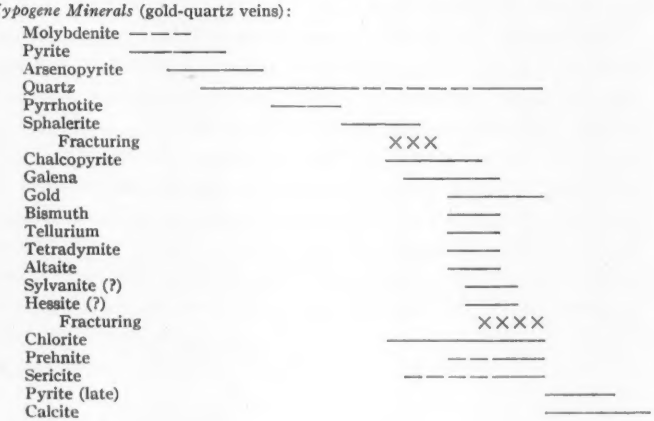
The ore minerals present are "persistent," and are found in deposits ranging from high to low temperature-pressure environments. However, arsenopyrite is more characteristic of the intermediate zone than of the shallow zone. These ores are considered to be mesothermal deposits because of abundance of

arsenopyrite and lack of diagnostic minerals of either the hypothermal or epithermal zones.

Gold-quartz Veins. The quartz-gold veins are pyrite and quartz with minor amounts of various sulphides, gold, tellurides and gangue minerals. The mineralogy of some veins is relatively simple consisting of quartz, pyrite, chalcopyrite, gold and calcite. Other veins contain a large number of minerals, but the paragenesis sequence follows a similar pattern for nearly all of the veins.

Mineralization of two widely separated periods is represented in these veins. The older veins, emplaced in pre-upper Cretaceous rocks are thought to be genetically related to post-Jurassic or early Cretaceous intrusives. The younger veins occur in Tertiary lavas and are believed to be genetically related to intrusives of late Miocene age. For comparative purposes a paragenesis diagram is given for each of these periods of mineralization. The late-Miocene (?) mineralization undoubtedly represents deposition at considerably less depth than the older period.

Polished sections from the older gold-quartz veins reveal two periods of fracturing which divide the mineralization into three stages. Early fracturing occurred near the completion of sphalerite deposition and the later fracturing followed near the end of galena deposition.



In the early stage pyrite, arsenopyrite and quartz were deposited in succession with overlap. All three minerals are in places automorphic against each other. Pyrite is dominantly automorphic, with arsenopyrite usually conforming to pyrite but dominantly automorphic against quartz. Quartz is occasionally automorphic against the others but may fill fractures in them. In some deposits quartz crystallization apparently ceased before pyrrhotite and sphalerite were deposited, although in others it continued into or possibly through the intermediate and into the third stage. Often there is no evidence of continual deposition, but quartz veinlets in galena cleavage fractures indicate a second generation of quartz crystallizing in the late stage.

Wherever pyrrhotite and arsenopyrite were associated, pyrrhotite veinlets in euhedral arsenopyrite furnish definite evidence that the pyrrhotite is younger.

Sphalerite deposition, if present, was followed by fracturing in nearly all the ores. Thus sphalerite appears to belong to the early stage. It was not observed as fracture-filling in pyrrhotite, but is enclosed as cavity-fillings by pyrrhotite or conforms to its outlines. Chalcopyrite, as dots and rods along sphalerite cleavage, is the only occurrence of chalcopyrite in the early stage and is probably due to exsolution.

The intermediate stage is characterized by a number of minerals that were deposited simultaneously or with overlap.

Chalcopyrite and galena, generally earlier than gold, conform to the outlines of earlier minerals or cut them as veinlets. Chalcopyrite-galena segmented veinlets cut sphalerite, pyrite and quartz; galena-quartz-gold veinlets cut pyrite.

Gold is rarely enclosed as dots and grains near the outer edge of chalcopyrite grains, and frequently as larger rounded grains it is enclosed by galena. Gold veinlets transecting galena-chalcopyrite boundaries are common. Gold and tellurides exhibit reversible relationships and are generally contemporaneous, but the frequency of gold veinlets cutting all of these minerals indicates that it continued to deposit after the late period of fracturing. Sylvanite and hessite are associated with gold in chalcopyrite at

the Chieftain and Continental mines. The tellurides display the same relationships to the older minerals as does gold.

Chlorite, sericite and prehnite have nearly identical relations and all appear to be developed in both the intermediate and late stages, although all three are best developed along fractures that were formed at or near the end of the intermediate stage.

A second generation of pyrite occurs as veinlets in many of the ores. It is later than some calcite as it follows calcite cleavage directions and may or may not be followed by later calcite.

Direct evidence bearing on the temperature-pressure environment in which these veins were deposited is scant. The veins are characterized by persistent minerals. Pyrrhotite is present in some veins as widely disseminated grains. Bismuth, present in the Irwin ore, is probably the only other diagnostic mineral. It is formed at temperatures not exceeding its melting point of 271° C.[25]

However, some information is available in the association of mineralized areas adjacent to or within granodiorite and quartz-diorite bodies. The quartz veins appear to be genetically related to the post-Jurassic intrusive rocks of the region. Intrusive rocks are present in the vicinity of many of the veins while the Ashland and Granite Hill orebodies are developed within intrusives.

If these intrusives and quartz veins were derived from the same parent magma, there was probably no extended hiatus between the deposition of the Ashland and Granite Hill orebodies and the solidification of their respective host rocks. In these cases, mineralization undoubtedly took place at a considerable distance below the surface. Likewise those veins in the vicinity of quartz-diorite or granodiorite intrusives, were probably deposited at considerable depths. This assumption is borne out by the present topography. There is a difference in elevation of approximately 6,000 feet between the lowest and highest points on exposed quartz-diorite bodies which are thought to be part of one large

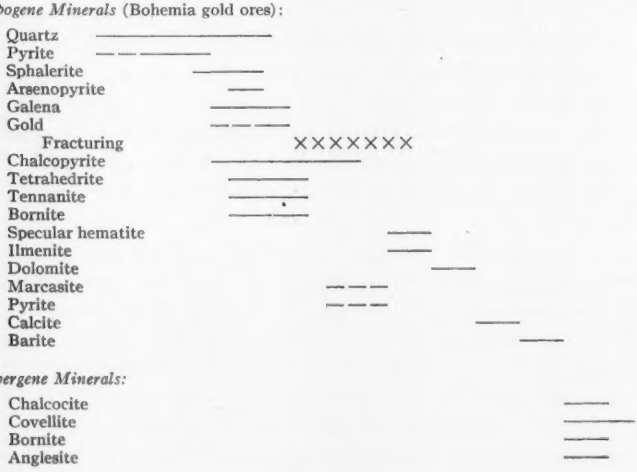
[25] Bowen, N. L.: Geologic Thermometry. The Laboratory Investigation of Ores. McGraw-Hill, New York, 1928, p. 179.

batholith underlying the region.[26] Therefore, erosion has removed at least 6,000 feet of overlying rock from some parts of the batholith without considering the thickness of the rocks into which the quartz-diorite was intruded.

Because of the lack of diagnostic minerals of either the hypothermal or epithermal zones and because topographical evidence points towards mineralization at considerable depth, most of the gold-quartz veins are considered to be mesothermal deposits.

The Tertiary gold-quartz veins are represented by the Bohemia area and by the Al Sarena and Barron mines (Fig. 1).

The following paragenesis diagram is similar to the one for the older gold-quartz veins, although several variations are readily seen. Several minerals, particularly the tellurides, are missing and new minerals have appeared.



An important variation is the late appearance of the high temperature minerals, specularite and ilmenite, which are present in the Bohemia veins but not in the Al Sarena or Barron veins.

[26] Wells: op. cit. (Grants Pass Quadrangle).

There are several other differences. Sphalerite and pyrite overlap. Sphalerite, galena and the copper-bearing minerals were deposited in an overlapping sequence in which sphalerite deposition began slightly earlier than galena, and galena deposition began slightly earlier than chalcopyrite. All three are in places automorphic against each other (Fig. 15). Galena, chalcopyrite, and tetrahedrite veinlets are common in sphalerite; chalcopyrite veinlets frequently cut galena; and tetrahedrite veinlets cut galena and chalcopyrite (Fig. 8). A tiny stringer of euhedral arsenopyrite is developed along a fracture in sphalerite but was not observed in other minerals.

Quartz deposition was continuous through the early and intermediate stages. It is automorphic against all the minerals and also conforms to most of the sulphides. Quartz and chalcopyrite crystals are perfectly developed in vugs where either may overlie the other.

In the early and intermediate stages mineralization seems to have been continuous, with the minerals overlapping. Before completion of galena and chalcopyrite deposition, fracturing occurred and the fractures were filled by these minerals and tetrahedrite.

The late stage in the Bohemia ore is characterized by introduction of specularite and ilmenite along contacts of earlier minerals, along contacts of "bands" in some banded and comb veins, and along fractures.

Specularite automorphically replaces all of the minerals except pyrite. It is best developed in quartz matrix and euhedral quartz, but needles transect sulphide boundaries (Fig. 6), cut sphalerite grains and intersect a chalcopyrite veinlet in sphalerite. Age relations of marcasite-pyrite veinlets to specularite are not decisive, although specularite appears to be later.

Carbonate deposition followed specularite. Fine-grained dolomite replaces quartz in some areas and cuts veinlets containing specularite. Rosettes of curving dolomite crystals are developed on quartz and chalcopyrite crystals in vugs. Calcite veinlets cut dolomite and lead to calcite crystals lining vugs.

The final stage was apparently completed by barite deposition. Barite crystals are developed in vugs and fractures but barite was not identified as forming part of the matrix. Its age relations to calcite are not certain as these two were not found in association although both line vugs and openings.

At the Al Sarena and Barron mines, the mineralization sequence is similar with the exception that deposition was completed in two stages. Carbonates were not identified in these ores.

Nearly all of the metallics in these veins are persistent minerals without diagnostic value. Tetrahedrite, marcasite and barite are characteristic of mesothermal and epithermal deposits while specular hematite is diagnostic of high temperatures. Tourmaline, epidote, johannsenite (pyroxene?) and adularia are reported to occur in the Bohemia district. Specularite, tourmaline, and johannsenite are high temperature minerals and are assigned to an initial high temperature stage by Callaghan and Buddington.[27] Adularia is reported to be characteristic of epithermal deposits.[28]

The mineralogy furnishes conflicting evidence for determining the temperature at which the veins were deposited, especially since the age relations of tourmaline, johannsenite and adularia to each other and to the other minerals are not known. Possibly the tourmaline and johannsenite are more closely related to the contact metamorphic zone than to the veins.

The writer believes that specularite is a late mineral in the Bohemia ores and that it indicates a high temperature period near the close of the mineralization period. Tourmaline and johannsenite may be related to this late high-temperature stage rather than to an initial high-temperature stage during vein formation. High temperature minerals have not been identified in the Al Sarena and Barron ores.

There seems to be a genetic relationship between the veins and small bodies of intrusive rocks that invade the Tertiary lavas.[29]

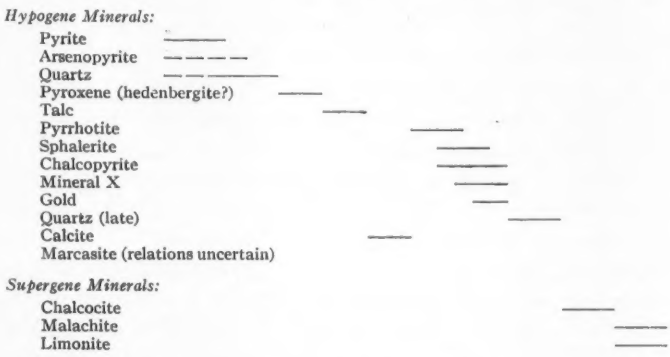
[27] Callaghan and Buddington: op. cit., pp. 23–28.
[28] Ore Deposits of the Western States, p. 36.
[29] Callaghan and Buddington: op. cit., p. 22.

The dioritic intrusives invaded lavas that have a maximum thickness of 6,500 feet in the Bohemia district.[30] Here the Champion and Helena veins (Bohemia district) cut the intrusives. Thus the evidence points to mineralization at moderate to shallow depths. The association of tourmaline, epidote and specularite led Buddington to classify at least part of the Bohemia veins as xenothermal.[31]

The writer believes that these veins are of the epithermal type, and that the late high-temperature stage in the Bohemia veins was due to late fracturing which permitted the influx of hot solutions from another portion of the intrusive body.

Paragenesis of the Pyrrhotite-Chalcopyrite Deposits.

The mineral sequence of the Waldo Copper ore is shown below. It is similar to that of the Fall Creek ore in that the dominant minerals—pyrite, pyrrhotite and chalcopyrite—have similar relations, while the arsenopyrite of the Waldo ore and the pentlandite of the Fall Creek ore occupy similar places in the mineral sequence. Sphalerite, gold and several nonmetallic minerals are present in the Waldo ore and not in the Fall Creek ore. The age relations criteria are similar to those already discussed for the gold ores.



[30] Ibid., p. 40.

[31] Buddington, A. F.: High-temperature mineral associations at shallow to moderate depths. Econ. Geol., 30: 219–221, 1935.

The diagnostic minerals are abundant pyrrhotite and the pyroxene (hedenbergite?), both characteristically developed in high temperature and pressure environments. The ores of the Waldo Copper mine and of Fall Creek are thus assigned to the hypothermal stage.

In the Fall Creek ore, polished specimens indicate that mineralization was subsequent to serpentinization. Magnetite and chromite grains and magnetite veinlets are common with the magnetite veinlets deceptively appearing to cut all sulphide minerals as well as cutting and rimming the chromite grains. Closer inspection shows that pyrite and pyrrhotite fill fractures in magnetite and chromite grains, cut magnetite veinlets, and pyrrhotite slightly replaces portions of the magnetite veinlets. Similar magnetite veinlets are developed in chrysotile grains of the serpentine in identical relationships. Serpentinization of olivine is often accompanied by a segregation of magnetite within fractures as minute veinlets.[32] Redistribution of the magnetite may result in still larger veinlets. Magnetite is a stable mineral under the high pressure-temperature environment involved and therefore it would be likely to persist in this deposit. These magnetite veinlets are interesting evidence that in rare instances the minerals of a vein may be *older* rather than younger than some of the minerals forming the vein walls.

Paragenesis of the Sphalerite-Chalcopyrite Deposits.

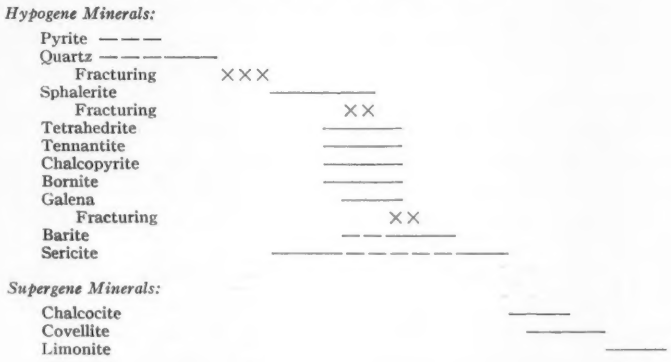
The mineral sequence of the Silver Peak ore is shown below. Ore from the Oak mine in which chalcopyrite is the only copper mineral present shows similar relationships.

Epidote, diagnostic of moderate temperatures, is the only diagnostic mineral and it was observed only in thin sections of the country rock adjacent to the mineralized zone. Evidence of higher temperature is the bornite-chalcopyrite intergrowth which, according to Schwartz, results only at high temperature (475° C.). However, the effects of time and pressure might have a

[32] Rogers, A. F., and Kerr, P. F.: Thin-Section Mineralogy. McGraw-Hill, New York, 1935, p. 174.

modifying effect on the temperature range at which such an intergrowth would form.

The epidote suggests that mineralization took place in the mesothermal zone, while the chalcopyrite-bornite intergrowth places the formation of the ore in the lower limits of the mesothermal zone, if not in the upper hypothermal zone.



Summary and Conclusions.

Paragenetic Sequence.

A more or less arbitrary classification of the veins was undertaken to simplify the paragenetic diagrams. First, the division was made according to the principal metal recovered, secondarily, on the most abundant sulphides present in each deposit. Thus copper ores are classified as pyrrhotite-chalcopyrite, and sphalerite-chalcopyrite deposits, and gold-quartz veins are divided into pyrrhotite-bearing, arsenopyrite-bearing, and pyrite-gold-quartz veins. The latter group is again subdivided into deposits occurring within pre-upper Cretaceous rocks and within Tertiary rocks.

The individual paragenesis diagrams for the mines show many variations, but when grouped according to the above classification the composite paragenesis diagram for each type of deposit retains the general characteristics of the individual diagrams. A comparison of these paragenesis diagrams for the various types

of deposits reveals a sequence that is characteristic for the entire area.

Nearly all of the diagrams exhibit an early, intermediate and late stage of mineralization, which may or may not be separated by fracturing. Fracturing is usually not severe and appears to result from minor adjustments within the veins.

The early stage is characterized by the successive deposition, commonly with overlap, of quartz, pyrite, arsenopyrite, pyrrhotite and occasionally sphalerite. One or two of these minerals may be absent.

Chalcopyrite, various other copper sulphides and galena follow in the intermediate stage, with sphalerite belonging more or less to both the early and intermediate stages. Gold, tellurides and bismuth are contemporaneous with chalcopyrite and galena at the end of the intermediate stage.

The late stage is characterized by carbonate deposition. Often a second generation of quartz or pyrite precedes the calcite. Marcasite accompanies late pyrite in the Bohemia area and is the latest mineral in the Al Sarena ore where carbonate was not identified.

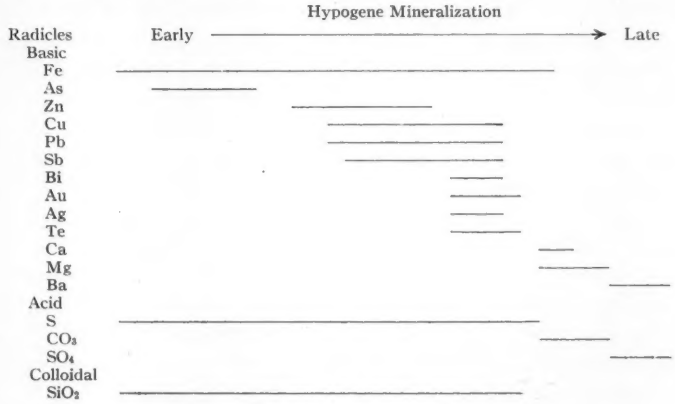
Some instances of replacement occur among the hypogene sulphides, mostly in the pyrrhotite-bearing deposits. Pyrrhotite replaces pyrite; chalcopyrite replaces pyrrhotite; and what appears to be a marcasite-pyrite intergrowth replaces pyrrhotite.

Calcite replaces arsenopyrite and chalcopyrite on a minor scale in the Jewett ore.

Although the mineralization sequence shows three stages, there is no evidence that an extended hiatus separated one stage from another. The younger minerals show late deposition by their conformity to crystal faces and outlines of the earlier minerals, by their deposition in vugs and cavities in ore already deposited, and by their occurrence in veinlets cutting the older minerals.

Although a few minerals are common in all of the ores, the presence of several others in only one or two mines produces a confusing picture if a composite paragenesis diagram is compiled for all of the mines. However, a paragenetic sequence in terms

of the radicles involved, as shown below, gives a fair interpretation of the hypogene mineralization for the region.



The deposits determined as hypothermal include the pyrrhotite-chalcopyrite deposits of the Waldo Copper and the Fall Creek mines, and the pyrrhotite-gold veins of the Humdinger and Frog Pond mines.

The mesothermal deposits include the sphalerite-chalcopyrite deposits of the Silver Peak and the Oak mines; the arsenopyrite-gold veins of the Peck, Anaconda and Warner mines; and the pyrite-gold-quartz veins which include most of the veins in the pre-upper Cretaceous rocks.

The gold-quartz veins in the Tertiary rocks are epithermal.

The order of deposition, as shown in the several paragenesis diagrams, is in accord with the sequence given by Lindgren.[33]

Hypogene Mineralizing Solutions.

Elements and Radicles in Solutions. The ore depositing solutions, which were active over so large an area, undoubtedly differed from district to district in the variety of radicles carried.

[33] Lindgren, Waldemar: Mineral Deposits, 4th edit. McGraw-Hill, New York, 1935, p. 122.

The mineralogy of the various deposits reveals at least a portion of the radicles that were being transported; others may have been present in the solution but were not precipitated in the veins.

The mineralogy of the various mines shows that the following radicles or compounds were deposited in the majority of the ores: Fe, As, Zn, Cu, Pb, Sb, Au, Ca, S, CO_2 and SiO_2. In addition, the solutions carried one or more of the radicles: Te, Bi, Ag, Mg, Ba, and SO_4. Water was presumably the most abundant component and its presence is demonstrated by the abundance of sericite, chlorite and epidote in many ores or in the adjacent wall-rock products.

Calcite, as the latest mineral deposited in nearly all of the ores, indicates that the solutions were alkaline at least in the late stage of mineralization. Marcasite as the last mineral at the Al Sarena mine indicates that the solutions there were cool and neutral or nearly so.

Temperatures. The diagnostic metallic minerals are pyrrhotite, native tellurium, and native bismuth. Pyrrhotite is diagnostic of high temperatures; tellurium and bismuth will not be deposited at temperatures higher than their melting points of 451° C. and 271° C. respectively.

Chalcopyrite occurs as an intergrowth with bornite that is similar to exsolution textures obtained by Schwartz at temperatures of 475° C. or higher. Another chalcopyrite intergrowth with an unidentified mineral similar to chalcopyrite-cubanite exsolution textures, may have a similar temperature range of formation.

A few high-temperature nonmetallic minerals—diopside, hedenbergite (?), orthoclase, microcline and garnet—are associated with some ores.

These diagnostic minerals are present only at a few mines. However, they indicate that the ore-depositing solutions in these instances possessed moderate to high temperatures, and since the mineralogy of all the deposits is similar and of hypogene character, it is a reasonable inference that all of the mineralizing solutions were hot in the early stage.

Source of the Solutions. Many of the veins in the Grants Pass area are close to exposed quartz-diorite and granodiorite bodies. The Ashland and Granite Hill mines are located within such intrusives. In the Grants Pass area these numerous small and large intrusives are thought to be exposed portions of one large batholith which underlies the region.

The mineralized belt in the Cascade Range parallels a belt of small dioritic intrusives and in some instances the veins cut both the intrusives and the invaded lavas.

Although the source of the mineralizing solutions which deposited the copper and gold orebodies cannot definitely be related to a given body of basic or acid rock, or even to a parent magma of both rock types, the frequent association of orebodies with quartz-diorite and related rocks has led to the conclusion that the mineralizing solutions are a late segregation product from a common parent magma.

Formation of the Veins. Most of the veins are lens- or tabular-shaped bodies of varying dimensions, seldom continuous for more than a few hundred feet. A few veins appear to fill fairly simple fractures; several of them, however, occupy more or less fractured or sheared zones enclosing considerable fragmented wall-rock and more or less gouge. Within their known extent they pinch and swell both horizontally and vertically. Movement along zones of weakness or fracture would produce openings of varying size. Many of the veins furnish evidence of pre-ore shearing by the presence of wall-rock fragments enclosed by unsheared vein minerals. Veinlets with matching-walls of younger ore minerals cutting older ore minerals indicate movements during ore deposition; and slickensided ore and gangue are evidence of post-ore movements. Thus the vein structures offer evidence that the veins are emplaced in faults, or shear zones which in many cases have been unstable previous to, during, and following ore deposition.

The textures and relationships of the minerals in the early, intermediate, and late stages of the paragenesis sequence point towards deposition in cavities by aqueous solutions. The earliest

minerals—pyrite, arsenopyrite and quartz—are commonly euhedral. The later minerals either conform to euhedral outlines of earlier minerals or fill fractures in them, and also as euhedral crystals are developed normal to vug and fracture walls.

Pyrite and occasionally chalcopyrite have been introduced into the wall rocks of some veins. Sericite, chlorite, epidote and calcite are the more common wall-rock alteration products. One, two, or all may be present in individual cases as alteration or replacement products of the wall-rock minerals. The alteration zones may be narrow, fairly wide, or even missing, but more or less parallel the vein and grade into country rock away from the vein. Thus the alteration zones show a genetic relationship to the veins.

The textures, the depositional sequence of the vein minerals and the wall-rock alteration seem to be explained most simply and easily by progressive crystallization from aqueous solutions, circulating through more or less open channels, in response to gradually changing physico-chemical conditions.

Outline of Mineralization.

Magmas have invaded the rocks of southwestern Oregon at least twice since Paleozoic times. The earlier igneous rocks consisting mainly of quartz-diorite and related rock were intruded into all of the pre-upper Cretaceous rocks. This period of intrusion accompanied or followed the mountain building epoch that uplifted the Sierra Nevada Range and adjacent regions. At the present time the numerous small and a few large bodies of these igneous rocks are thought to be part of one large batholith underlying much of the Grants Pass Quadrangle and adjoining areas.

Sometime during the Miocene epoch, magma again intruded parts of the area. This intrusion is known from small bodies and dikes of igneous rocks that intrude and metamorphose Eocene sediments and Miocene lava flows along a narrow north-south trending belt in the western part of the Cascade Range.

Preceding, during, or following these intrusions the intruded rocks were subjected to fracturing or faulting. These fracture and fault systems served as channels for the aqueous solutions given off late in the crystallization of the magma.

The ore-bearing solutions moved upward and outward through fissures, fractures, shear zones and permeable rock zones to deposit ore and gangue minerals. Because the channels were more or less discontinuous the resulting quartz veins are lens-shaped-tabular bodies. The continuity of the original channels and many physico-chemical factors influenced the deposition of the ore—in places resulting in high-grade ore deposits but in other places only in lean or barren quartz.

CHICAGO, ILLINOIS,
June 15, 1942.

LEACHED DERIVATIVES OF ARSENOPYRITE AND CHROMITE.

ROLAND BLANCHARD.

ABSTRACT.

The minerals arsenopyrite and chromite are unusual genetic associates but their leached derivatives possess a common characteristic. The arborescent pattern or structure of their limonitic pseudomorphs is of far bolder relief and more uniform persistence than is found in limonitic derivatives of other sulphides or ore minerals. The pseudomorphs are described, the more prominent types illustrated with photographs, and analytical data are presented to show the major chemical and mineralogical changes which take place during oxidation and leaching of the two minerals.

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INTRODUCTION.

ARSENOPYRITE and chromite are not often genetically associated but arsenopyrite was later and small in amount in the one place

the author has observed the two side by side in nature. Leached derivatives of the two minerals have certain characteristics in common however, and are described together in this paper.

Derivatives of arsenopyrite have been studied over an extended geographic and climatic range, with widely varying primary sulphide intergrowths and associations, but derivatives of chromite (for purposes of this paper) have been studied only from the serpentine belt of New Caledonia. Important deposits of chromite in strongly oxidized regions elsewhere, with a similar host to the one prevailing in New Caledonia, make a description of the isolated New Caledonian derivatives appropriate at this time when the search for ores of chromium is world wide.

The characteristic feature common to preserved derivatives of both arsenopyrite and chromite is the arborescent pattern or structure of the limonitic pseudomorphs, with resultant high relief. When viewed under $\times$ 10 to $\times$ 20 magnification the structures stand out as objects in a stereoscope. Limonitic derivatives from other minerals exhibit the characteristic to a limited degree in restricted types of products, but none has been found to exhibit it with the spectacularly bold outline, the uniform persistence, and the freedom from contamination by other products, which characterize the derivatives of arsenopyrite and chromite.

DERIVATIVES OF ARSENOPYRITE.

Two broad types of arsenopyrite occurrences, based upon the resultant leached derivatives, are recognized: (1) arsenopyrite-pyrite mixtures essentially free from other base sulphides; (2) more complex sulphide mixtures in which arsenopyrite is an important and often the predominant sulphide constituent.

Arsenopyrite-Pyrite Mixtures Essentially Free From Other Base Sulphides.

Apart from its arborescent pattern, the oxidized derivative of arsenopyrite-pyrite mixtures differs in several other respects from limonitic products heretofore described in the Leached Outcrops papers. The product has a dry crinkly appearance, and to that

extent resembles cellular sponge of sphalerite derivation. It is not cellular, but consists of a porous clinkery mass made up of loosely-aggregated but firmly-joined granules. The greenish-yellow to faded olive drab color of many of the granules suggests the presence of scorodite.

Nature of the Freshly Oxidized Derivative.—In the freshly-oxidized phase a limonitic or limonitic jasper groundmass is profusely studded and intimately intergrown with numerous and often predominant granules of scorodite. These range in size from less than 0.1 to 0.5 mm., with the smaller generally prevailing. They are mostly granular, but grade into the characteristic blunt orthorhombic crystal form with corroded edges, and have resinous to sub-resinous luster. The sub-resinous luster usually extends to the limonitic granules as well. The whole mass is bound together by minute intergrowths of limonitic jasper, which make the product clinker-like and give it high rigidity. SiO_2 content normally varies from 10 to 25 per cent.

Most of the scorodite occurs as an indigenous precipitate as does much of the limonitic material. Presumably the limonitic matter is derived mainly from oxidation of the admixed or associated pyrite, and precipitated by gangue neutralizer, as it is rarely well preserved in quartz gangues even though scorodite may be abundant.

Under the hand lens the mass does not consist of compact, uniformly dispersed granules like marbles in a bag, but is built up largely of small branching clusters or knob-like projections of the granules. The projections occur in unsymmetrical shapes 2 to 3 mm. in height, which usually exceeds by several times their habitually variable thickness. They are disposed indiscriminately toward one another with total disregard for pattern or orientation, giving rise to a highly porous, shapeless aggregate. In rare instances the projections take the form of slender fragile excrescences, with one grain after another (usually of scorodite) perched precariously upon the preceding, like a column of blocks in a child's nursery; but in general, the more stubby type of projection prevails. The final product is a structureless

arborescence of high rigidity and rugged relief, which, once identified, is not readily confused with any other leached precipitate.

A variation from the projections described above is the frequent growth, at irregular intervals through the mass, of isolated, minute, hollow, green to pale olive hemispheres. Less frequently the shape is semi-elliptical to bluntly concave. The diameter of the hemispheres rarely exceeds 1 or 2 mm., and under × 10 to × 20 magnification the growths resemble tiny scooped-out green half oranges, with walls or shells composed of micro-granules of scorodite free from limonitic admixture. Frequent parasitic encrustment of the mixed scorodite-limonitic material beneath leaves no doubt that they represent a transported phase of essentially pure scorodite. The hemisphere structures crumble more readily upon exposure to weathering than the underlying intergrown scorodite-limonitic material. This tends to accentuate the aborescent pattern of the total mass, but at most contributes only a subsidiary effect.

Several noteworthy features serve to differentiate the product from leached derivatives of other sulphide origin. One is the virtual to complete absence of cellular boxwork or cellular sponge. In photographs an apparent cellular sponge exists (Fig. 1), but this is merely a shadow effect. The mass itself is composed entirely of the loosely-aggregated granular projections.

Another feature is that the leached product derived from a high-arsenopyrite-low-pyrite mixture has more abundant scorodite embedded in or scattered through the loosely-aggregated mass than one derived from a low-arsenopyrite-high-pyrite mixture.

Observations over widespread occurrences show that, irrespective of the total amount of arsenopyrite originally present, a large proportion of the arsenic is retained as scorodite within the leached derivative. In thoroughly oxidized fresh material the proportion of retained arsenic may be more than one-half. Even in strongly leached material, which field evidence suggests may have been exposed to weathering for several centuries, as much

as one-fourth of the original arsenic may be retained. The proportion is only slightly less in inert quartz gangues from which the iron derived from oxidation of the pyrite has been completely exported. Since the arsenopyrite and pyrite decompose more or less contemporaneously in these sulphide intergrowths, it must be concluded that during the decomposition processes (1) arsenic is less mobile than iron, and (2) the two sulphides, even as fine intergrowths, commonly oxidize side by side without vital interference from their oxidation solutions during formation of the respective leached derivatives.

FIG. 1. Typical oxidized derivative of a gold-bearing massive arsenopyrite-pyrite mixture whose ratio was approximately 1 ar:2 py. The minute granules of scorodite and limonitic matter are clearly visible. The limonitic matter includes many small scattered specks or blebs of limonitic jasper which serve to bind the granular mass into a rigid whole, and impart to it a clinker-like feature. The stubby projecting clusters of tiny granules mentioned in the text are not fully discernible without greater magnification, but their general presence throughout the mass is indicated by the specimen's pronounced relief. No cellular structure is present; the pseudo-cellular structure is produced by shadow effects obtained in photographing. Enterprise property, Hodgkinson Goldfield, Queensland. $\times 2$.

That some interplay of the solutions occurs is strongly suggested, however, by the fact that under none of the field conditions noted has the scorodite failed to show corroded crystal edges, that the degree of corrosion increases in general with increase in proportion of pyrite in the parent mass, and that with other conditions equal, corrosion is greatest in quartz gangues where the acid solutions derived from oxidizing pyrite normally would attain their highest concentration. The interplay of solutions is further suggested by the partial mergence of the scorodite granules along their contacts, and by the semi-resinous luster which usually is conspicuous upon all freshly-formed limonitic particles within the granular mass.

Effects of Continued Weathering.—It is noteworthy that in oxidized material exposed for a long period to weathering, if a knob or other excrescence composed largely of scorodite granules is attached to a limonitic jasper base, it tends to corrode and perforate the jasper by "eating" holes into it at the point of attachment. This not only increases porosity of the granular mass as a whole but often causes the more delicate projections to collapse. Some of the collapsed projections are carried away by mechanical erosion; others tend to "glue" themselves discordantly to the underlying mass, accentuating further the loosely-aggregated arborescent structure.

Although scorodite persists in the leached derivative under the most severe weathering a slow replacement of the mineral by "limonite" nonetheless takes place. Under magnification of $\times$ 20 to $\times$ 30 the initial attack upon an individual granule appears spotty, somewhat resembling the skin of a boy with large and excessive freckles; thereafter the limonite laboriously spreads over most or all of the scorodite grain.

The limonitic mineral in such case is rarely composed of supergene jasper; usually it comprises the softer goethite or lepidocrocite, with tendency for the individual granules to shrivel slightly as replacement proceeds and become more distinctly globular. When an entire cluster or knob-like projection becomes thus affected, the shriveling may bring about compaction until

the original granular knob stands out like a tiny stalagmite (Fig. 4).

With continued weathering most of the scorodite-limonitic mixture alters finally to a dark brownish-black product, with occasional Indian-red to copper-red limonitic patches, and occasional apple-green ferrous arsenate stains resembling the malachite-green coatings of weathered native copper. At that stage of decomposition the resemblance to a strongly-weathered mottled arborescent cluster of native copper crystals is striking.

Despite the changes above noted, the process of limonitization has never been complete for specimens approaching hand size, and no instance has been noted in which the arsenic, as scorodite, has been wholly leached, or otherwise completely removed by weathering, from an outcrop whose parent sulphide carried several per cent arsenopyrite.

The Disseminated and Thinly-Dispersed Sulphide Type.—The above descriptions apply to semi-massive to massive arsenopyrite-pyrite mixtures, in which the two sulphides constitute 10 per cent of the rock as a minimum, and in which the sulphides are to some extent concentrated as nodules or as replacement aggregates.

If the amount of the two sulphides is well below 10 per cent, and they either are disseminated or occur as narrow seamlets so that a large area of neutalizer in the rock is consistently in contact with a small area of sulphide, the leached derivatives still largely retain their identifying characteristics; but the limonitic jasper may give way to a more pulverulent or fluffy type of simple hydrated ferric oxide. This applies particularly if the gangue possesses moderately strong neutralizing power, as feldspar or limy shale. Such derivatives of arsenopyrite-pyrite mixtures, possessing little or no limonitic jasper to act as binder, disintegrate more rapidly under weathering processes, and in outcrops subjected to long erosion the derivatives may lose most of their identifying characteristics.

Wiluna (Western Australia) affords an instructive example. At Wiluna the run-of-mine ore carries approximately 2 per cent

arsenopyrite and 3 per cent pyrite. Although the sulphides are concentrated or aggregated within the oreshoots in varying degree, much of the sulphide occurs minutely disseminated through an effective neutralizing gangue of calc-schist. Thus at the surface it is often difficult to distinguish, with the unaided eye or under the ordinary hand lens, which of the leached products has been derived from arsenopyrite and which from pyrite. The matter is of economic significance, because at Wiluna the gold is associated almost wholly with the arsenopyrite,[1] and areas of dominantly pyritic origin have little or no prospecting appeal.

An external feature, however, assists in the identification. Many of the arsenopyrite disseminations are bluntly acicular, whereas the pyrite ones are granular to cubic. Outcrops yielding an abundance of pseudo-acicular casts therefore may be regarded as favorable, even though the casts may have been vacated of their leached derivatives, or the derivatives may have become too disintegrated to be interpreted intelligently. But even under Wiluna conditions, many of the casts in material protected from severe weathering yield grains of scorodite which are readily identifiable as such under the hand lens.

Complex Sulphide Mixtures in Which Arsenopyrite is an Important Constituent.—Derivatives from arsenopyrite in the more complex sulphide mixtures retain the granular intergrowth of scorodite and limonitic particles as an identifying feature. Three additional characteristics serve to distinguish them from the

[1] H. H. Carroll, general manager of Wiluna Gold Mines Limited, has kindly made available the following figures, which are of general interest wholly aside from their relationship to the Leached Outcrop studies:

APPROXIMATE ARSENIC-GOLD RATIOS IN WILUNA ORE.

290-ft. level	—	1% As	:	8.47	dwt.	Au	per	ton
450-ft. "	—	"	:	7.53	"	"	"	"
625-ft. "	—	"	:	5.17	"	"	"	"
800-ft. "	—	"	:	3.17	"	"	"	"
1000-ft. "	—	"	:	2.94	"	"	"	"
1200-ft. "	—	"	:	2.12	"	"	"	"
1400-ft. "	—	"	:	2.94	"	"	"	"
1600-ft. "	—	"	:	2.35	"	"	"	"
1800-ft. "	—	"	:	2.47	"	"	"	"
2400-ft. "	—	"	:	2.23	"	"	"	"
2700-ft. "	—	"	:	1.30	"	"	"	"

simple arsenopyrite-pyrite-derived product: (1) a greater or lesser development of cellular boxwork emerging irregularly from

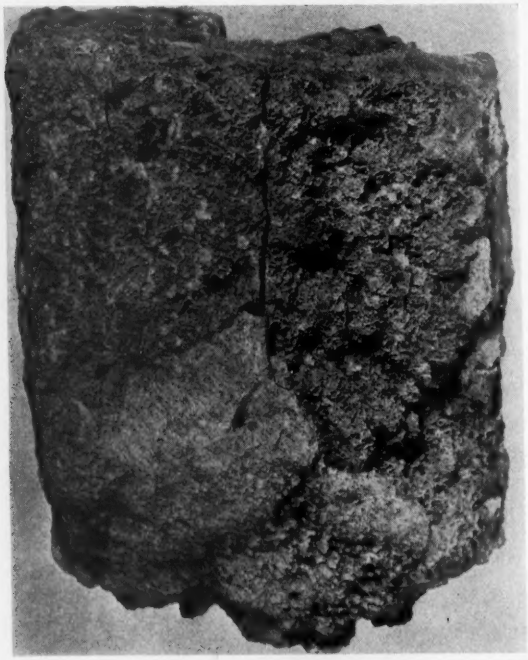

FIG. 2. Example of cellular boxwork emerging from a granular scorodite-limonitic matrix. Parent of the leached derivative in this case consisted of an arsenopyrite band ¼ in. thick in a complex sulphide banded intergrowth corresponding in general to composition of Specimen 2, Table 1. In this case, with pyrite-pyrrhotite content low and with additional adjoining complex sulphides present, scattered boxwork structure has developed in a pattern conforming to the fracture and cleavage of arsenopyrite. The granular projections occur mostly as slender arborescent excrescences, rather than as the stubby knob-like structures of Fig. 1. Their delicate inter-joining produces, at numerous places, a distinctly fragile granular fretwork. Specimen from near Moore Shaft, Conrad Mine, New South Wales. × 1.5.

the granular mass; (2) a more fragile composition of, and a far more loose interconnection between, the granular particles or projections, resulting in what often constitutes in effect granular fretwork; (3) common association and intergrowth, with such granular projections, of oxidized minerals other than scorodite and the limonitic group.

Cellular Boxwork.—Distinct cellular boxwork structure emerges from the porous granular mass infrequently, with an individual occurrence seldom exceeding 1 or 2 cm. in length. Its main ribs are composed chiefly of limonitic jasper, though intergrowths of scorodite occur. The latter usually increases toward the periphery, so that the boxwork often merges insensibly into the surrounding granular material. Thickness of the boxwork ribs normally is 0.01 to 0.1 mm., seldom attaining 0.25 mm. Cell diameter rarely exceeds 0.5 mm.

Cross webs of the boxwork usually are poorly defined, and are feebly joined to the main longitudinal ribs. They always make an obtuse angle with the latter, presumably reflecting the prismatic cleavage of arsenopyrite. Scorodite generally predominates over limonitic jasper in their composition. Thickness of the cross web wall seldom exceeds 0.05 mm. Examples of well-defined and freshly-formed boxwork are furnished in Figures 2 and 3.

In banded sulphide deposits the boxwork appears to develop as freely within seams of arsenopyrite up to one-half inch thick as it does in environments of intimately intermixed complex sulphide composition.

Although distinct cellular boxwork does not develop prolifically, the hand lens discloses throughout the more granular portions many incipient ribs which parallel in a general way the main boxwork structure. Their length rarely exceeds 5 mm. Like true boxwork, they form initially along cleavage or fracture planes of the decomposing arsenopyrite. Their limonitic jasper content invariably is low, however, and they grade so imperceptibly into the granular excrescences that clear-cut distinction between the two products is often difficult. They give the impression of

FIG. 3. Specimen showing a more general development of granular fretwork within the scorodite-limonitic matrix; also numerous incipient fine ribs which terminate as granular excrescences insead of developing into true boxwork. At several places, also, the boxwork itself may be observed merging with surrounding granular material along its peripheries. Where granular fretwork is well developed, as in this specimen and in Fig. 2, minute granules of mimetite often are intergrown with the scorodite, usually in much lesser amount, rendering the granular projections even more fragile. Specimen represents a large leached massive arsenopyrite nodule at its contact with intergrowths of galena, sphalerite and minor pyrite-pyrrhotite. The original sulphide environment corresponds in composition closely with that of Specimen 5, Table 1, but no derivatives indigenous after galena or sphalerite are here involved. Silver Ridge property near Kajabbi, Queensland. ×2.

having started out as true boxwork ribs but, through inability to incorporate into their compositions sufficient limonitic jasper, not only have they been unable to project themselves boldly forward, but usually have been unable to maintain, against the surrounding arborescent encroachments, their modest rib-like beginnings.

Thus, while boxwork, both in the incipient form and as distinctly ribbed structures, forms during decomposition of arsenopyrite in the complex sulphide mixtures, and in some instances is conspicuous, it never attains dominance, and it constitutes only a subordinate feature for identification of the parent sulphide.

Granular Fretwork.—The chief identifying feature continues to be the granular scorodite-limonitic matrix, but it differs from that of arsenopyrite-pyrite origin.

In derivatives of arsenopyrite in the complex sulphide mixtures, there is not only a far more abundant development of the slender, fragile, columnar, granular excrescences as compared with the stubby knob-like structures, but—primarily because of that fact—the projecting structures are joined to one another so lightly that they often resemble fretwork. Because there is a higher percentage of scorodite than of limonitic granules in the more slender projections, the clinker-like feature of the whole mass is less pronounced than is true if arsenopyrite and pyrite are the sole sulphides.

Not only do the slender structures constitute a large proportion of all projections present within the granular mass, but they commonly encrust themselves upon the boxwork cell walls as well. Many of them are so small they become distinctly visible only under $\times$ 10 or greater magnification. But although always unsymmetrical in shape, the more fragile ones (especially those developed within cell cavities of the boxwork) rival in delicacy and beauty of outline the most fantastic of snowflake crystals. When these delicate growths become limonitized by weathering, the snowflake structure contracts notably, and becomes much more compacted and globular, as snowflakes do when contracting into nevé.

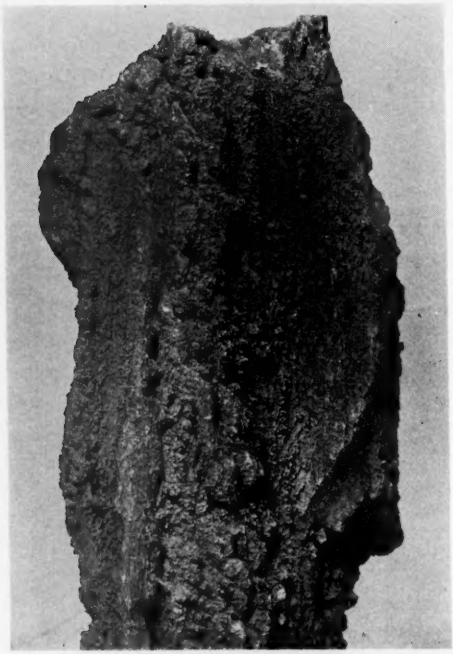

FIG. 4. Strongly leached and strongly weathered derivative of a large arsenopyrite-pyrite nodule which occurred originally in a mixed complex sulphide evironment. With increased weathering the limonitic jasper boxwork has become corroded and pitted at points of attachment with the slender scorodite excrescences, so that the original longitudinal ribs of the boxwork now have become a series of interrupted chains of arborescent projections. Leached derivatives with chains of arborescences, as in this case, have been found only where mimetite exceeded 5 per cent of the material within the freshly oxidized phase. Not infrequently the mimetite subsequenly breaks down, under continued weathering, decomposing in part into earthy massicot.

In this specimen the projections have become largely replaced by limonitic matter, and much of the arsenic has segregated into local precipitations or encrustments of apple-green ferrous arsenate. Note that in protected portions of specimen the strongly arborescent shapes have been preserved, whereas in portions exposed to prolonged weathering they

The large number of scorodite projections or excrescences commonly attached to the limonitic jasper walls of the boxwork structures, with their corroding action upon the jasper, renders the boxwork readily vulnerable to weathering, and it is not uncommon in advanced stages of weathering to observe the longitudinal ribs with successive perforations, like holes in a colander. Eventually complete breaches in the ribs occur, and a succession of chains of the perforations may develop.

In time the entire mass of granular material becomes transformed into the limonitic stalagmites described earlier. If the rib structure previously was well developed, the final result may be a succession of roughly parallel rows of the stalagmites, as in Figure 4. The stalagmites in this case, however, usually are more profusely coated with minute arborescences than is the case in derivatives from simple arsenopyrite-pyrite mixtures, because of the much greater original number of fragile excrescences.

The question may be asked why boxwork develops pseudomorphously after arsenopyrite only in derivatives from the complex sulphide mixtures, and why the slender columnar (mainly scorodite) projections are so much more prolifically developed than in the arsenopyrite-pyrite mixture.[2]

The high acidity of solutions derived from the oxidation of pyrite is well established as a deterrent to the formation of cellular structure other than sponge, as evidenced by the types of limonitic product universally yielded by oxidizing pyrite. Even in the (rare) cellular sponge of pyrite derivation the cell wall thickness nearly always exceeds diameter of the cell cavity, tending to reduce the structure toward the botryoidal or the flat,

[2] The author is not prepared to assert that cellular boxwork may not develop where the sole decomposing sulphides comprise arsenopyrite and pyrite, but in observations extending over many years he has failed to find them.

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have contracted into the more stubby type of projection. Contrast the clinker-like feature of this specimen with the virtual freedom thereof in No. 3. In this specimen a high percentage of pyrite originally was intermixed as sulphide, giving rise upon limonitization to extensive formation of limonitic jasper. Mount Bonnie mine near Grove Hill, North Australia.

smeary type of limonitic crust which so generally characterizes the leached product precipitated in a strongly acid environment.

In the more complex sulphide mixtures, the proportion of pyrite, relative to the arsenopyrite, is often less than in the simple arsenopyrite-pyrite mixtures. Even if such is not the case, the high-acidity effects of its solutions are likely to become dissipated through partial intermingling with solutions or products of decomposing sulphides other than arsenopyrite. The arsenopyrite thus is more nearly free to oxidize without external interference, and the leached derivative likely to be patterned more closely after its parental cleavage or fracture form.

The real test of the above suggestion would be to observe the oxidized derivatives yielded by decomposing arsenopyrite with which no other sulphide was associated, and from which, during its decomposition, acid solutions from an external source were rigidly excluded. The author has encountered no such occurrences in nature.

Whether the suggestion offered above constitutes the fundamental explanation for the limitation of cellular boxwork, and for the usual limitation of prolific development of the slender columnar scorodite-limonitic projections to derivatives of the more complex sulphide mixtures, the author is not prepared to state. At least it embodies one explanation which seems valid.

Intergrown Extraneous Minerals.—In the earlier investigations into derivatives from oxidizing arsenopyrite only the scorodite-limonitic granules and the less frequent development of limonitic jasper boxwork were noted. In outcrops specifically derived from the more complex sulphide mixtures, however, abnormal amounts of PbO often were disclosed in the analyses. Pseudomorphs after crystalline cerussite were rare or absent in all of the outcrops, and although the characteristic "partially sintered" limonitic crusts of globular cerussite derivation were not uncommon, such material usually was precipitated adjacent to rather than within pseudomorphic limits of the decomposing arsenopyrite. The amount within such limits failed to account for more than a small proportion of the PbO present. Occa-

sional crystals of pyromorphite, and more rarely of phosgenite, were observed, but in most cases they were clearly distinguishable as parasitic, and could be excluded from the material for analysis. Yet PbO continued to persist strongly in many of the analyses. Detailed microscopic work, confirmed by analyses of selected material, eventually disclosed that most of the PbO left within pseudomorphic limits of the oxidizing arsenopyrite was present as mimetite.

The mimetite is scattered through the leached derivative, often as minute single grains, rarely in blebs or aggregates up to 1 mm. across. Its color blends into the faded olive drab of scorodite, commonly the mineral particles are globular rather than crystalline, and where crystal form is developed the edges often are corroded even more than are those of scorodite, making recognition of the hexagonal-pyramidal crystal form difficult. Added to these factors is the mineral's more ready replacement by "limonite," which makes it difficult to distinguish from decomposing scorodite except in freshly oxidized specimens.[3]

The mineral usually represents only a fraction of the percentage of scorodite present, but in exceptional cases it has constituted 10 to 15 per cent of the total oxidized product, as in specimens from the Conrad and Mount Bonnie mines noted in Table 1.[4] Its chief significance as an intergrowth with the scorodite-limonitic granules is that the usually smaller grain size and more ready susceptibility to decomposition, renders the granular excrescences still more fragile, causes them to break down irregularly under weathering, and thereby accentuates the arborescence of the final leached product. The pattern of Fig. 4, for example, has been observed only in outcrops whose less leached phases carried upward of 5 per cent mimetite intergrown with the scorodite-limonitic granules.

[3] Familiarity with the mineral in the oxidized derivatives is best made by microscope study, after which its identification under the hand lens becomes easier.

[4] In these two instances, and at Mount Emu, the parent minerals are more heterogeneously intergrown with one another than at the other mines listed in Table 1. The condition is indicated by the high percentage of indigenous cerussite present. In such an environment mimetite content often is greater than usual.

TABLE 1.

ANALYSES AND PROBABLE MINERALOGICAL COMPOSITION OF GALENA-ARSENOPYRITE SULPHIDE ORES AND THEIR DERIVED GOSSANS.

STATE.	NEW SOUTH WALES.					QUEENSLAND.					NORTH AUSTRALIA.				
PROPERTY.	CONRAD.			COMMONWEALTH.		SILVER RIDGE.				MOUNT EMU.	IRON BLOW.			MOUNT BONNIE.	
Specimen No. Sulphide Ore or Rock Oxidized Equivalent Strongly Leached Equivalent	1.	2.	2a.	3.	3a.	4.	5.	5a.	5b.	6a.	7.	7a.	7b.	8a.	8b.
Analysis															
Au Dwt.	tr.—1	1.1	1.0	4.43	4.1	.9	5.7	3.8	4.1	n.d.	4.2	3.7	4.1	1.62	1.16
Ag oz.	20.05	37.6	2.2	5.92	tr.	3.2	13.0	.72	nil	n.d.	13.6	tr.	tr.	1.1	tr.
Pb %	8.42	13.5	15.9	3.55	.65	.75	7.2	5.4	1.05	11.2	3.0	1.2	.7	14.8	5.4
Zn %	2.10	3.3	1.1	12.05	tr.	1.6	3.2	tr.	nil	.55	5.4	.35	tr.	1.05	tr.
Cu %	1.39	2.7	tr.	.75	.25	n.d.	n.d.	n.d.	n.d.	n.d.	.43	tr.	tr.	n.d.	n.d.
Sn %	1.06	2.1	tr.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
As %	6.00	14.4	11.1	6.70	3.85	3.0	18.3	13.5	4.4	3.9	4.9	3.7	1.8	11.15	6.2
Fe %	6.35	12.8	19.1	27.10	39.4	6.6	17.1	25.7	34.9	38.5	30.25	37.5	42.4	16.1	25.8
S %	7.16	13.0	tr.	35.6	tr.	6.0	13.25	tr.	nil	nil	35.0	nil	nil	tr.	nil
Mn %	n.d.	n.d.	tr.	n.d.	.3	n.d.	n.d.	nil	nil	tr.	n.d.	.14	.45	1.6	1.8
Cl %			.375		.02			.16	.005	.12	nil	.035	tr.	.20	.085
Al_2O_3 %			2.8								n.d.	4.3		9.2	7.0
SiO_2 %			17.8								n.d.	19.7		21.0	23.4
Insol. %			n.d.	9.5	18.1	68.4	32.6	21.6	24.3	13.0	n.d.		20.3		
CaO %			nil		tr.			n.d.	n.d.	n.d.	nil	nil	nil	.4	.1
MgO %			tr.		.02			n.d.	n.d.	n.d.	.14	tr.	nil	tr.	tr.
CO_2 %			1.3		.15			tr.	nil	1.7	tr.	.21	nil	2.5	.2
Additional O*			19.67		25.48			26.08	23.035	24.19		23.775	24.94	19.50	20.575
Probable Mineralogical Composition															
Sphalerite	3.15	4.93		19.0		2.39	4.78				8.06				
Galena	9.7	15.58		4.1		.87	8.31				3.46				
Stannite	3.85	7.63													
Chalcopyrite	.7	1.25		2.15							1.24				
Arsenopyrite	13.0	31.25		14.55		6.52	39.74				10.64				
Pyrrhotite	1.3	1.08		.25		3.26	3.37				2.35				
Pyrite	.7			45.65		4.91	2.85				53.24				
Tennantite (est.)	.075	.10		.025											
Smithsonite			1.70					tr.		.86		.54		1.60	tr.
Cerussite			4.25							8.57		.13		10.13	.73

Chalcopyrite	.7	1.25		2.15							1.24					
Arsenopyrite	13.0	31.25		14.55		6.52	39.74				10.64					
Pyrrhotite	1.3	1.08		.25		3.26	3.37				2.35					
Pyrite	.7			45.65		4.91	2.85				53.24					
Tennantite (est.)	.075	.10		.025												
Smithsonite			1.70					tr.		.86		.54		1.60	tr.	
Cerussite			4.25							8.57		.13		10.13	.73	
Mimetite			15.635		.86			6.67	.21	5.00		1.45	tr.	8.40	3.55	
Massicot			.63					.40	.89	.19			.70		2.13	
Malachite					.44											
Scorodite			26.92		11.45			38.48	13.47	9.67		10.71	5.54	30.43	17.43	
Calcite equivalent														.71	.18	
Country rock (est.)														18.00	15.00	
Limonitic jasper			40.01		75.39			46.89	73.12	68.79		78.08	84.35	28.22	51.54	
Miscellaneous			10.855		11.86			7.56	12.31	6.92		9.09	9.41	2.51	9.44	
	32.475	61.82	100.000	85.725	100.00	17.95	59.05	100.00	100.00	100.00	78.99	100.00	100.00	100.00	100.00	

NOTE:

1. For Nos. 2*a*, 3*a*, 5*a*, 5*b*, 6*a*, 7*a*, 7*b*, 8*a* and 8*b*, Pb and Zn figures of the analyses are for PbO and ZnO respectively.
2. For scorodite, malachite, and the goethite or lepidocrocite content of limonitic jasper, calculated O includes water of crystallization.
3. Limonitic jasper, as calculated, excludes adsorbed and capillary water.
4. Miscellaneous comprises in large part adsorbed and capillary water of the limonitic minerals.
5. Specimen No. 1. Average composition of sulphide ore along 4600-ft. continuously stoped section of Conrad lode. Average depth of sampled sections 300 to 400 feet. Country rock, granite. Conrad mine near Inverell, New South Wales.

No. 2. Representative high grade ore, free from banded sulphides, at NW end of Conrad lode, near King shaft.

No. 2*a*. Thoroughly oxidized but not strongly leached equivalent of No. 2.

No. 3. Average composition of sulphide ore along 200-ft. × 28-ft. (maximum dimensions) lens of Commonwealth lode, 85-ft. level; based upon channel sampling of three crosscuts through lens. Country rock, replaced slate along slate-quartz-porphyry contact. Commonwealth mine near Wellington, New South Wales.

No. 3*a*. Representative thoroughly oxidized but not strongly leached outcrop over No. 3.

No. 4. Channel sample across 5-ft. low grade portion of 6-ft. Silver Ridge lode. Excludes 1-ft. band of heavy sulphide. Main shaft, 45-ft. depth. Country rock, sericite schist. Near Kajabbi, Queensland.

No. 5. Channel sample across 1-ft. heavy sulphide band of above lode. Main shaft, 45-ft. depth.

No. 5*a*. Thoroughly oxidized but not strongly leached equivalent of No. 5. Main shaft, 8-ft. depth.

No. 5*b*. Strongly leached equivalent of No. 5. Outcrop at main shaft.

No. 6*a*. Representative thoroughly oxidized but not strongly leached galena-arsenopyrite ore from a 3-in. to 18-in. width of Granite Castle reef. Country rock, slightly greisenized granite. Mount Emu, Queensland.

No. 7. Representative ore from 170-ft. × 35-ft. (maximum dimensions) North lens, 100-ft. level, Iron Blow mine. Country rock, chloritic schist. Near Grove Hill, North Australia.

No. 7*a*. Thoroughly oxidized but not strongly leached equivalent of No. 7.

No. 7*b*. Strongly leached equivalent of No. 7*a*.

No. 8*a*. Representative thoroughly oxidized but feebly leached ore from 70-ft. × 25-ft. (maximum dimensions) lens, 200-ft. level, Mount Bonnie mine. Country rock, slate-mica schist. Near Grove Hill, North Australia.

No. 8*b*. Strongly leached equivalent of No. 8*a*.

* Per cent of O calculated to complete mineralogical computations.

Tables 1 and 2 prove that mimetite is not a freak or isolated development in the oxidation of the complex sulphide mixtures described, but forms over a broad geographic and climatic range.[5]

TABLE 2.

SHOWING GEOGRAPHIC AND CLIMATIC FEATURES OF LOCALITIES FROM WHICH SPECIMENS OF TABLE 1 WERE OBTAINED.

Property.	Approximate Latitude and Longitude.	Approximate Elevation in Feet above Sea Level.	Average Annual Rainfall Inches.	Rainfall Distribution.	Climate.
New South Wales					
Conrad	30° S 151° E	2200	32	Moderately uniform throughout year; slight concentration November–March	Temperate; light snow and frost in winter
Commonwealth	32¾° S 148¾° E	1150	23	Moderately uniform throughout year; slight concentration November–March	Temperate; light snow and frost in winter
Queensland					
Silver Ridge	20° S 140° E	700	18	75% December–March	Sub-tropical; arid most of year
Mount Emu	20° S 144¾° E	2300	24	70% December–March	Sub-tropical; arid most of year
North Australia					
Iron Blow	13½° S 131° E	300	50	85% December–March	Tropical; hot and humid 8 months of year
Mount Bonnie	13½° S 131° E	400	50	85% December–March	Tropical; hot and humid 8 months of year

[5] In Table 1, average composition of sulphide ore for several of the properties is furnished, to show that specimens selected for the respective sulphide, oxidized, and strongly leached phases are representative. In some cases the mine workings were not accessible at time of visit. In such cases the most representative sulphide material obtainable on the dump at the surface, or, if unobtainable, the most representative freshly oxidized material which agreed with the mine's known production, was selected. In the oxidized specimen transported or parasitic matter was excluded from the material for analysis; so far as the crushed material could be

A noteworthy feature is the presence of earthy dull-yellow massicot as a further decomposition product of the mimetite in many of the strongly leached specimens. Usually the amount is small, but ½ to 1 per cent is not uncommon. Its occurrence in arid and semi-arid regions seems natural, and the mineral is by no means rare in Australia.[6] Its identification as a leached derivative of mimetite at such places as the Conrad and Commonwealth mines of New South Wales under temperate conditions, however, with rainfall well distributed through the year (Table 2), shows that its occurrence is not limited to the more arid regions, to specific types of country rock, or circumscribed by specific geographic or climatic conditions.

DERIVATIVES OF CHROMITE.

The author has not visited the New Caledonian chromite deposits. Specimens of the ore and leached material herein described were collected and submitted by Richard Quirk, assistant mine manager, Societe la Tiebaghi (Tiebaghi mine) at Paagoumene. Descriptions of the chromite occurrences, together with their geological setting and the conditions surrounding their oxi-

freed from extraneous substances, only matter which could be strictly classified as indigenous gossan, was used.

Oxidized specimens were crushed and examined under the hand lens for evidence of pyromorphite, phosgenite, etc., and chlor-arsenates other than mimetite were segregated in the few instances found. Cl then was determined to the nearest 0.005 per cent, and total Cl was assumed to exist as mimetite. Content of mimetite, as thus calculated, agreed reasonably well with visual estimates of the mineral made with the hand lens in the specimen or as a crushed powder.

[6] In small amount massicot is associated with mimetite in outcrops of the silver-lead-zinc orebodies at Mount Isa. At the Longamundi property, 56 miles NE of Mount Isa, it constitutes 95 per cent or more of the lead minerals along a 15- to 50-ft. wide lode which is intermittently exposed for more than 5,000 ft. From three trenches along a 1,650-ft. length of the lode, each 3 to 10 ft. deep, the author obtained by channel sampling an average 30-ft. width yielding 2.94 per cent Pb (3.74 oz Ag), of which one 5-ft. cut yielded 9.1 per cent Pb (8.4 oz Ag). A selected specimen yielded 19 per cent Pb. (Subsequent trenching and sampling by the Aerial Geological and Geophysical Survey of Northern Australia yielded up to a 50-ft. width of 8.7 per cent Pb (5.22 oz Ag) per ton.) At Longamundi the massicot occurs mainly as joint- and fracture-plane fillings, from a knife-edge to 1 in. thick, in an irregular stockwork in graphitic shale.

dation, have been supplied by Quirk and by L. E. Sinclair, general manager of Societe Chimique du Chrome (Fantoche mine) at Nehoue. Both men are former field associates of the author.

The Tiebaghi serpentine dome, as described by them, extends from Koumac northwesterly to Nehoue Bay, a length of approximately 12 miles and a width of approximately 3 miles. Its southwesterly flank runs more or less into the sea and its northeasterly flank passes inland beneath Tertiary schists which form the valley of the Nehoue river. The dome's maximum elevation (Tiebaghi mine) is 1,900 feet.

The workable deposits of chromite occur as irregular pipes within the serpentine. The Tiebaghi pipe locally occupies an area up to 100×200 feet, and has been proved to a depth of 1,300 feet. The Fantoche pipe is developed to approximately the same depth.

An iron capping extends over practically the whole dome area, with no pronounced preference for the known deposits of chromite. The capping occurs as nodules, boulders and sustained masses. It generally overlies a layer of decomposed serpentine, and not infrequently is impregnated with grains of chromite. In accordance with topography, capping varies in thickness from 1 inch to 100 feet.

Origin of the capping as a whole is not established. Some of the submitted material is merely weathered gossan without identifying features, and probably represents the sub-lateritic to lateritic decomposition of either the serpentine host, or one of the later intrusives which appear to have been, in the main, the bearers of the chromite;[7] possibly it represents lateritic decomposition of both. Two types of the submitted gossanous material, however, may be traced pseudomorphously into the fracture pattern or other structural form of the chromite. Deri-

[7] Sinclair states that at the Fantoche mine the vein formation is clearly later than that of the host rock, evidenced by wall alteration of the chromite-serpentine contacts, together with instances of the ore grading into unmineralized serpentine. Both at Fantoche and Tiebaghi the serpentine shows a pronounced change at the same vertical depth below the surface ($825 \pm$ ft.), though the significance thereof is not clearly understood.

TABLE 3.

ANALYSES AND APPROXIMATE MINERALOGICAL COMPOSITION OF CHROMITE ORE AND ITS DERIVED GOSSAN, NEW CALEDONIA.

Analyses.

Specimen.	% Pb.	% As.	% Cr_2O_3.	% Ni.	% Fe.	% Mn.	% S.	% Al_2O_3.	% SiO_2.	% CaO.	% MgO.	% CO_2.	% SO_3.	% Ignition Loss.
No. 1. Massive chromite	nil	nil	59.6	0.4	10.0	0.2	0.16	13.9	6.0	1.8	1.4	1.4	nil	n.d.
No. 2. Nodular chromite studded through serpentine matrix	nil	nil	44.1	1.0	9.5	0.2	0.2	9.7	13.2	0.1	14.6	tr.	nil	n.d.
No. 3. Leached derivative of No. 1	nil	0.013	3.8	tr.	8.8	1.9	—	1.8	72.2	nil	tr.	0.2	nil	7.7
No. 4. Leached derivative of No. 2	nil	0.013	2.19	tr.	6.7	.7	—	4.0	79.0	nil	tr.	0.7	nil	3.6

Approximate Mineralogical Composition.

	No. 1.	No. 2.	No. 3.	No. 4.
Chromite	74.0	57.8	4.8	2.84
Spinel constituent (Al_2O_3)	13.9	9.7	?*	?*
Calcite	3.2	.15	—	—
Free quartz	5.7	—	—	—
Nepouite	1.1	—	—	—
Nickeliferous serpentine	—	31.5	—	—
Supergene carbonate gangue	—	—	.5	1.8
Limonitic jasper	—	—	89.5	92.7
S, unallocated	.16	.2	—	—
As, unallocated	—	—	.013	.013
Undetermined	1.94	.65	—	—
Miscellaneous †	—	—	5.187	2.647
	100.00	100.00	100.000	100.000

* Part of Al_2O_3 probably present as spinel associated with chromite. For convenience all Al_2O_3 has been included with the limonitic jasper, as most of it, especially in No. 4, probably occurs in that association.

† Mainly adsorbed and capillary H_2O associated with the Fe_2O_3 and MnO_2.

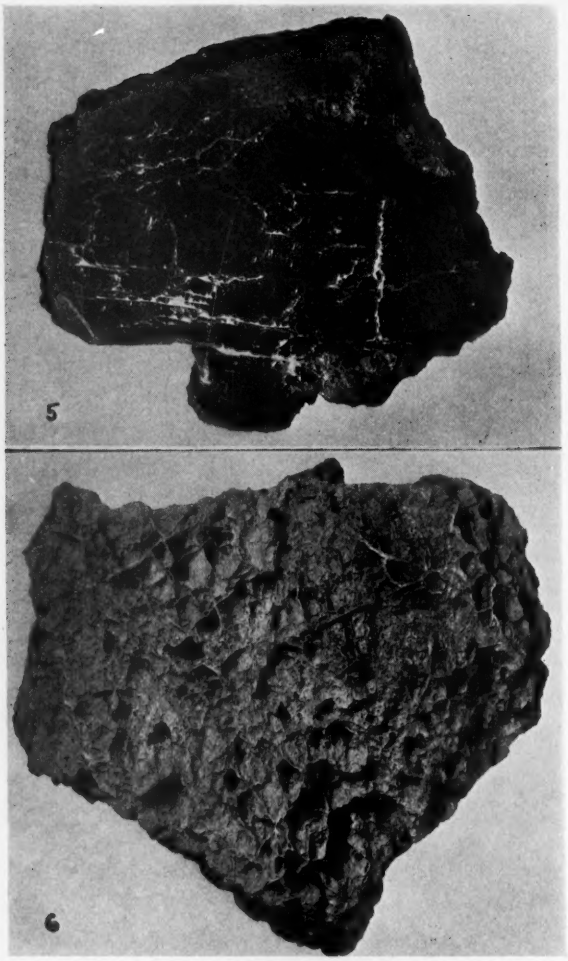

FIG. 5. Polished section of Tiebaghi massive chromite, showing inherent fracture pattern. Analysis corresponds to that of Specimen 1, Table 3. Much of the Tiebaghi massive chromite has associated with it a decomposed feldspar which disintegrates readily at the touch. In

vation of those two types therefore is not in doubt. The two types comprise a massive phase of chromite, and an occurrence in which nodules of chromite up to ⅕ inch or more across are studded through the serpentine matrix.

Massive Chromite.

Honeycomb Boxwork.—Upon decomposition the massive chromite forms a conspicuous coarsely cellular honeycomb boxwork with cell diameter as much as ¼ inch across. The boxwork clearly patterns itself after the fracture system of the chromite, as shown by Figs. 5 and 6. The fracture system, in turn, appears to be guided in part by chromite's octrahedral crystal form (Fig. 5), but the relationship usually is poorly defined.

The cross ribs are well joined, as would be expected in honeycomb boxwork, and the resulting structure is rigid and coherent. Thickness of the boxwork walls commonly varies from less than 0.01 to 0.2 mm., with 0.5 mm. maximum. Analyses of Table 3

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this specimen all such material was purposely segregated before analysis, and the SiO_2 content of the analysis represents predominantly hypogene quartz. Under the microscope minute platy grass-green crystals of nepouite were observed in the chromite. Presumably they account for all of the nickel of the analysis. Tiebaghi mine, New Caledonia. Natural size.

FIG. 6. Leached equivalent of Fig. 5. Note how the coarse cellular boxwork or honeycomb, comprised of limonitic jasper, has followed closely the fracture pattern disclosed in the chromite of Fig. 5. Many of the coarse cells are filled with the dried-out "bran mash" limonitic material which, under weathering, usually shrinks away slighlty from the coarser boxwork walls. The limonitic filling is composed of a minutely cellular sponge, with cells as small as 0.005 mm., and averaging probably not more than 0.02 to 0.035 mm., in diameter. Under erosive processes the coarser cellular boxwork becomes largely vacated of its sponge filling, but a thin coating of the latter invariably adheres to the boxwork walls. To the unaided eye the adherent material may appear to be finely pulverulent. With magnification upward of $\times 30$ however, it reveals itself as tiny arborescent limonitic excrescences which usually are joined loosely together to produce the airy and tenuous sponge structure described in the text. Analysis for Fig. 6 corresponds to that of Specimen 3, Table 3. Tiebaghi mine, New Caledonia. Natural size.

show that the boxwork is formed of a limonitic jasper exceptionally high in SiO_2.

Minute Cellular Sponge.—The boxwork, if not exposed to severe weathering, is filled with an indigenous, drab-ochreous, minute cellular sponge. Like the honeycomb boxwork the sponge is made up of limonitic jasper, but its SiO_2 content generally is lower (20 to 40 per cent) than that of the coarser boxwork, and its Fe_2O_3 content much higher (25 to 45 per cent).

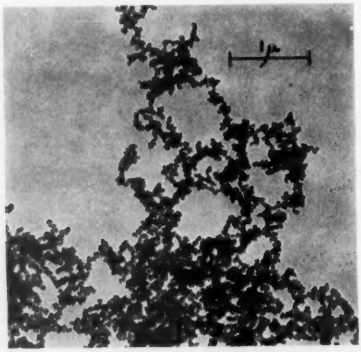

FIG. 7. Carbon black deposited from the smoke of burning benzene. Micrograph taken with the electron microscope. × 12,500.

The irregular cellular pattern, produced by the random joining together of smoke granules which build upon one another as fragile arborescent excrescences, resembles closely the cellular pattern yielded as limonitic sponge by decomposing chromite. The chief difference is that in the sponge of chromite derivation the excrescences or cell walls, instead of comprising granules, are composed of minute crinkled limonitic crusts or flakes, resembling "cornflake" breakfast food.

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The sponge, as a mass, tends to shrink away from the boxwork walls, and resembles small blobs of dried-out bran mash. Continued weathering crumbles the shrunken portion and much of it is carried away, but a thin coating of sponge invariably ad-

heres tenaciously to the boxwork walls. Usually it is so fine-celled that it appears pulverulent to the unaided eye.

The minute size of the sponge cells may be judged from the fact that on a 5-mm. length of line across one of the coarser boxwork structures the author counted, under the microscope, 263 individual cells of sponge resting end to end, making their

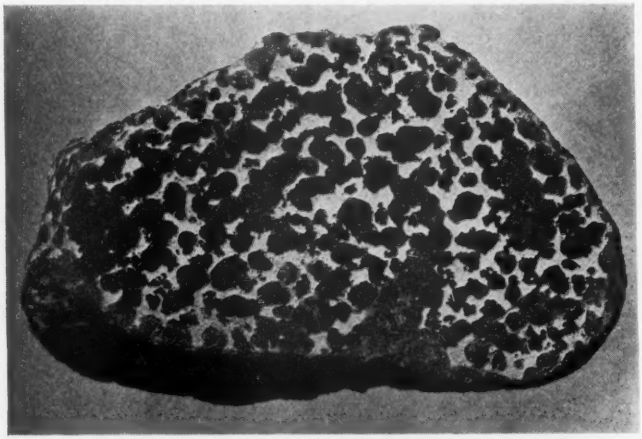

FIG. 8. Polished section of nodular chromite disseminated in a serpentine matrix. In other respects the chromite is similar to that of Fig. 5. Analysis for Fig. 8 corresponds to that of Specimen 2, Table 3. No nepouite was observed; the nickel of this specimen is thought to be present as nickeliferous serpentine. Tiebaghi mine, New Caledonia. ×1.2.

average diameter 0.019 mm. As the cells are highly variable in size the diameter of some of them is much less than 0.019 mm.; cells of 0.005 mm. diameter have been observed. Since cell wall thickness normally is one-third to one-fifth the cell diameter, but may be only one-tenth, that of the sponge structure lies between 0.006 and 0.002 mm., and may be less (Fig. 6). Therefore it is not surprising that without magnification much of the cellular sponge appears pulverulent.

In addition to its minute size the sponge differs in several respects from an ordinary limonitic cellular product. There are no through-going ribs or webs patterned closely after the parent mineral's fracture or cleavage planes, as in the coarser honeycomb structure, and no orthodox cell wall pattern exists. The sponge is made up of innumerable flaky excrescences which join loosely and at random into an airy and tenuous, arborescent fretwork, much as do the carbon black particles of Fig. 7. The main difference is that the sponge particles do not comprise crystals or granules but consist mostly of crinkled limonitic crusts or flakes, which resemble "cornflake" breakfast food in miniature. Though usually requiring at least × 30 magnification to be seen, the limonitic sponge of chromite derivation yields one of the most outstanding arborescent patterns among the leached outcrop products. The existence of cellular structure within it is primarily the result of the characteristic random joining-up of the minute fragile limonitic flakes, rather than of a webwork patterned directly after grain boundaries of the decomposing mineral.

Nodular Chromite Studded Through a Serpentine Matrix.

Nodular chromite studded through a serpentine matrix, upon decomposition, forms the same types of limonitic derivatives as does massive chromite. Well-defined honeycomb boxwork is rare because of the small size of the nodules and the limonitic residuals as a whole are less well preserved because the serpentine decomposes contemporaneously with the chromite.

The serpentine is found in all stages of decomposition. In well-weathered material little remains of it except an amorphous-looking, smoky to chocolate-colored jaspery mass with somewhat corroded hexagonal crystals up to 1 mm. long and ½ mm. wide (usually smaller) which project at random into space. The crystals, though resembling quartz in other respects, usually contain a (low) percentage of Fe_2O_3, and thus border upon limonitic jasper.

A well-defined cast after the chromite nodule does not remain because much of the serpentine has recrystallized into

supergene limonitic jasper masses with small projecting crystals. For the same reason the cavity often becomes grossly distorted in shape (Fig. 9), and much of the limonitic honeycomb and sponge which forms indigenously after the decomposing

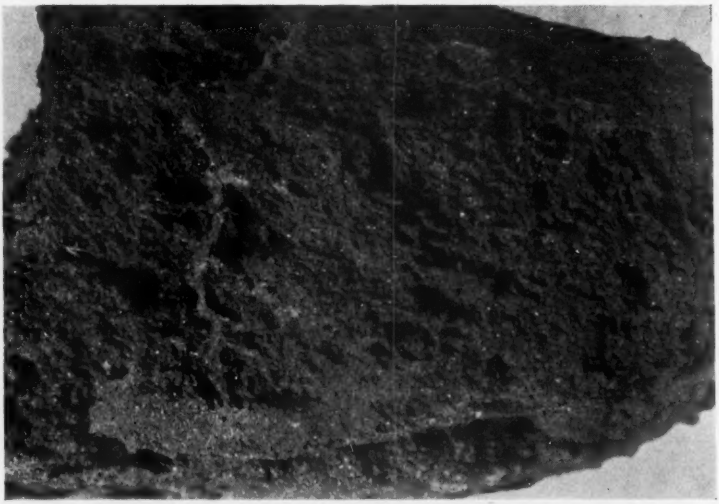

FIG. 9. Leached equivalent of a specimen generally similar to Fig. 8. The serpentine has been largely recrystallized into smoky-brown to chocolate-coloured limonitic jasper, with discordantly-arranged, small smoky-brown quartz-jasper crystals projecting from it. Casts left by the decomposing chromite nodules thus have become distorted in shape. Most of the cavities or casts retain as an indigenous product some of the minute limonitic cellular sponge, as evidence that chromite constituted the nodular parent. Analysis for Fig. 9 corresponds to that of Specimen 4, Table 3. Tiebaghi mine, New Caledonia. ×2.

chromite is lost. Decomposition of the chromite generally lags slightly behind that of the serpentine at any given place however, and remnants of the sponge may be preserved within the reformed cavity to serve as a clue. Such remnants must be interpreted cautiously, as serpentine far from ore areas often carries,

or at one time carried, small amounts of chromite (and nickel; see Table 3) disseminated sparsely through it. By breaking adjacent material less exposed to erosion it may be possible to determine more closely the percentage of chromite originally present, and thus arrive at a more accurate estimate as to the possibilities for commercial exploitation.

Although the residual limonitic derivatives after disseminated nodular chromite, which has decomposed in a serpentine matrix, do not furnish as accurate an index for appraisal of the leached area for prospecting as do the more homogeneous and better preserved derivatives after massive chromite, a clue nonetheless is present which often may be intelligently followed.

Observations Upon Decomposition of Chromite in Nature.

The leaching of chromite in New Caledonia is neither universal nor deep-seated; local persistence of the unaltered mineral to the surface through a strongly weathered lateritic soil led originally to discovery of the principal oreshoots of the Tiebaghi dome. The analyses of Table 3 coupled with microscopic work, likewise show that in small amount chromite grains remain unaltered even in the most thoroughly leached material submitted. Nonetheless, well defined leaching of the mineral extends in some areas to depths of more than 30 feet.

In view of the widely-held belief that chromite is immune to ordinary weathering attack,[8] and because of the supporting fact that it is common as a residual in placer deposits, it is in order to inquire whether the New Caledonian leaching phenomenon constitutes a special condition.

The author seriously doubts it. His observations over broad geographical areas and over an extended period of time show that leaching phenomena exhibited in one district or on one continent are closely duplicated in other districts and upon other continents, although local environments and climatic conditions admittedly

[8] Lindgren, Waldemar: Mineral Deposits, 4th edition, p. 785; Emmons, W. H.: Principles of Economic Geology, 2nd edit., p. 431; U. S. Geol. Surv. Bull. No. 625, p. 423.

induce modifications of the general features. Until data from other chromite districts are presented by competent observers to substantiate or repudiate the author's opinion, however, conditions, so far as known, which may place the New Caledonian phenomenon in a special class should be considered.

Of the various important known surface exposures of chromite those of New Caledonia appear to be the principal ones occuring in the tropics under conditions of active laterization. Efficacy of the weathering and lateritic processes upon the island are attested by the residual surface concentrations of garnierite and other supergene nickel minerals from the much lower grade nickeliferous serpentine, and by extensive decomposition of the serpentine itself. How effective those processes may have been in decomposing the chromite, the author is not prepared to state.

In the text accompanying Fig. 5 it was pointed out that much of the Tiebaghi chromite has associated with it a feldspar which crumbles readily at the touch. In material prepared for analysis of Specimen 1, Table 3, all visible feldspar was excluded. Even granting that small undetected amounts remain, they in no way can account for the Al_2O_3 content of the analysis. Since no other aluminous minerals were observed, it must be concluded that the Al_2O_3 is present as a chrome spinel, probably in solid solution with the chromite since only one chrome mineral has been observed. The fact that the ratio of Al_2O_3 to Cr_2O_3 of Specimen 2, Table 3 is nearly identical with that of Specimen 1, and that in Specimen 2 no directly identifiable aluminous mineral of any sort was observed, corroborates the suggestion of a solid solution admixture of chromite and a chrome spinel high in alumina content, in the New Caledonia product.

Such admixtures are not uncommon in chromite deposits, and data from other districts are needed to determine whether the ratio at Tiebaghi is out of line with that existing elsewhere. Data also are needed to determine whether such admixtures, in any ratio, favor more rapid decomposition than do the individually purer components thereof.

At present the author is inclined to discount both of the above factors as important contributors in the decomposition of chromite, and to have faith that careful search will yield evidence of substantial chromite leaching in districts other than New Caledonia. But a final conclusion is not warranted.

The chrome leaching phenomenon existing along the Tiebaghi dome seems significant enough, in any event, to justify close inspection of leached outcrops in other chromite districts, to assure that important deposits of the mineral may not have been overlooked.

MOUNT ISA MINES LIMITED,
MOUNT ISA, QUEENSLAND,
June 11, 1942.

DISCUSSION AND COMMUNICATIONS

ORIGIN OF CHILEAN NITRATE DEPOSITS.

Sir: With greater caution and less confidence than in 1916, I venture to return to a discussion of the origin of the Chilean nitrate deposits. The paper by Rich in the May number of ECONOMIC GEOLOGY is not only an interesting description of the localization of the nitrate deposits based on a new point of view, as seen from an airplane, but ranks as one of the important contributions to the problem of their genesis. It challenges features of the theory proposed by Singewald and Miller in 1916 so strongly as at least to demonstrate that the ultimate explanation of the occurrence of these deposits must be more complex than so simply outlined by them. On the other hand, Rich clearly recognizes that the theory of Whitehead, which he accepts as best in accord with the facts, may still leave the problem unsettled.

A rereading of literature prior to 1916, and a review of the literature since 1916, impresses upon one the remarkably small amount of both specific and comprehensive geologic observations contained in that voluminous literature. It is surprising that there is not only not a detailed geologic description of these deposits as a whole, including areal geologic mapping, petrographic and chemical investigations of the rocks, and detailed sections of the deposits from surface to bed rock, but there is not available in the literature even such an account of one of the fields. There are enough data in the literature to show that the details of the occurrences are not identical throughout the region. All of us who have speculated on the origin of these deposits have had our paths made easier by this lack of disconcerting details in the literature and by the lack of adequately comprehensive first hand observations. Theories based on only part of the facts, or on broadly

generalized data, or on detailed knowledge of a small part of a large region, are inevitably vulnerable. Such has been the fate of the many theories that have been advanced to explain these nitrate deposits.

Due to the lack of areal geologic maps to support such a conclusion, one cannot be sure of a spatial and causal relation between the character of the underlying or adjoining rock and the localization of the nitrate deposits. Lindgren (p. 26), asserting that the dependence of the nitrate on the extent of certain Jurassic intrusions, effusives and tuffs is so clear that there must be some genetic reason behind it, admits his acquaintance is superficial. There is no reason for not accepting Whitehead's observation, based on detailed work in the Aguas Blancas field, that in Aguas Blancas three tuffaceous beds are particularly favorable loci, and that intrusive rocks and strongly silicified tuffs are not favorable loci (p. 210), but even he notes exceptions elsewhere. Sundt, depending on the underlying rock for the formation of the nitrate merely as a source of sodium, recognizes a less restricted dependence and requires merely the presence of feldspathic porphyrites. It is not obvious why acidic lavas are considered unfavorable, nor why the abundant and widespread soluble sodium salts are not an adequate and available source of soda wherever nitric acid may be formed or accumulated in the region. Brüggen categorically states there is no relation between the occurrence of nitrate and the character of the underlying rock. He states the nitrate and its accompanying salts are found in and above rocks of such different character as porphyrites, granodiorites, limestones, gravels, sands, and clays (p. 226).

Because volcanic exhalations emit and volcanic rocks occlude nitrogen compounds, the weathering of the volcanic rocks of the nitrate region offers a plausible and probably important source of the nitrate. There is nothing at variance with the theory of Singewald and Miller in the acceptance of this assumption. That theory disclaims any attempt to determine the source of the nitrate and restricts itself to the mode of its accumulation. If nitrates were derived from these Mesozoic rocks, then their widespread

occurrence and their tuffaceous facies were favorable to the contribution of nitrates to the waters of the region, whether surface waters or underground waters. Strongly supporting such a probability is the observation by De Kalb in the Rodeo Valley of New Mexico, where in the Peloncilla Range, on the east side of the valley, under thick rhyolite effusives, rhyolite tuffs are incrusted with nitrate. But no workable concentrations formed here, indicating that conditions peculiarly favorable to concentration are as much a *sine qua non* as a nitrate source. There are many other localities in reasonably arid regions where volcanic tuffs are abundant, but where not even nitrate incrustations have formed. Hence one would wish for determinations of the nitrogen content of the Chilean volcanics and comparisons of their nitrogen content with that of similar volcanic rocks in other regions. Moreover the Chilean volcanics are more widespread in the Chilean deserts than are the nitrate deposits. One would wish for a comparison of the nitrogen content of these volcanics where nitrate deposits occur and where they do not occur.

Dr. Edward B. Mathews has just completed a compilation of analyses of igneous rocks of the world as a project of the Geological Society of America. They include only 11 analyses in which nitrogen and nitrogen compounds were determined. All of them are in the Eastern Hemisphere, and all but one are of volcanic rocks. In a granite from Indo China 0.57 per cent N_2O is reported. Four NH_3 determinations from Stromboli are:

	NH_3
Scoria	trace
Leucite tephrite ashes	0.01%
Leucite tephrite ashes	0.03
Leucite tephrite	0.24

Two analyses of volcanic ash from Krakatoa show 0.01 and 0.02 per cent N. Four analyses of phonolites from Baratonga Island in the Cook Isles show 1.08, 1.14, 1.20, and 1.20 per cent NO_2. This meager record does not indicate a higher nitrogen content in volcanic clastics than in lavas. It is so largely confined to

nepheline and leucite rocks, that it gives no information concerning any tendency there may be toward higher nitrogen concentrations in particular rock types. The analyses do show that volcanic rocks are a possible source of nitrate. They show that Whitehead's assumption (p. 219) of a content of 0.02 per cent NH_4Cl is quite reasonable and plausible. Hence one need not hesitate to accept the volcanic rocks of the nitrate region as an important or even the major source of the nitrate in the deposits. The establishment of this fact proves nothing, however, regarding the way in which the nitrogen content of the volcanic rocks was concentrated into the nitrate deposits. The concentration may have been brought about by surface moisture and waters in the manner described by Whitehead. On the other hand, this widely disseminated nitrogen content may have found its way into the underground waters of the region and been concentrated in the manner postulated by Singewald and Miller. The manner of concentration must be proven in each case apart from the proof of the source of the nitrate.

The association at Aguas Blancas of nitrate and certain tuffs is suggestive of a genetic relation and makes these tuffs a plausible source. However, the association of the nitrate deposits with these tuffs and their lack of association with intrusive rocks and strongly silicified tuffs is susceptible of another explanation. The tuffs afford a porous basement, more penetrable by evaporating ground waters that might be the source of the nitrate. Hence until those tuffs are demonstrated to be peculiarly rich in nitrogenous substance, they can only be regarded as a plausible rather than a proven source of the nitrate at Aguas Blancas. Beyond Aguas Blancas, the association is less well established, the spatial relation less close, and even denied.

Descriptions of the actual relations between the nitrate and the underlying bed rock are not as specific and clear, nor as abundant, as one might expect in literature on deposits of such great economic importance. There is essential unanimity, however, regarding the generalized vertical section. Beneath a practically salt free surface covering, are three gradational layers, *chuca,*

costra, and *caliche,* consisting predominantly of sulphates in the *chuca,* decreasing amounts of sulphates and increasing amounts of chlorides and increasing but minor amounts of nitrate in the *costra,* and maximum and workable amounts of nitrate in the *caliche.* Beneath the *caliche* is the *coba* which consists of fractured rock or gravels. Whitehead (p. 205) states the *caliche* is "usually sharply defined from loose gravels lying below." The gravels are like the typical desert debris of the region. Whitehead describes these gravels as dry and not cemented but often containing a little salt. Where they have a high salt content they are called *congelo.* He states the salts in the gravels beneath the *caliche* are sulphates and chlorides. Semper and Michels (p. 370) describe the *coba* as a loose, generally somewhat moist earth mixed with small stones. Its salt content is generally low and consists predominantly of sodium sulphate and chloride. Between the *caliche* and the *coba* commonly occurs the *congelo* layer which is a rock breccia containing sodium chloride and sulphate as the most abundant salts. Rogers and Von Wagenen (p. 9) likewise state that the *caliche* does not generally lie on bed rock, but is commonly underlain by loose unconsolidated fine gravel and sand. Brüggen (p. 229) describes the *coba* as a loose reddish earth, often a little moist and with a small content of salts. Rich (p. 203) emphasizes the dry and porous nature of the material beneath the *caliche* whether it be gravel, sand, or broken bed rock.

The thicknesses of these different layers varies greatly. All of the layers are not represented in all sections of the deposits. In places, especially toward the up-hill margin of the deposits, the *caliche* lies on the bed rock or even impregnates disintegrated bed rock. On the other hand, Semper and Michels (p. 371) state that wells drilled in Tarapaca show thicknesses of *coba* up to 100 m. There is also at least a general change in thickness, richness, and height above bed rock of the layers impregnated with the salts. A diagrammatic representation of these relations is given in figure 4 of Semper and Michels (p. 373). This diagram shows the highest level margin of the *caliche* lying on broken bed rock in thin and discontinuous patches. It thickens progressively at

lower elevations to the edge of the salar. At the same time it is underlain by increasing thicknesses of *coba*. On the other hand, the *costra* has a maximum thickness at its highest level and decreases in thickness progressively in the direction of the salar. The nitrate tenor of the *caliche* bed decreases as the bed thickens. These changes are shown quantitatively on the diagram in two vertical sections near the highest level and near the lowest level of the *caliche* bed. The sections are:

	Near Top	Near Bottom
Chuca	0.30 m.	0.30 m.
Costra	2.40	0.30
Caliche	0.30 (60% $NaNO_3$)	0.90 (22% $NaNO_3$)
Congelo	0.10	0.10
Coba	thin	thick

This diagram does not conform exactly to the lateral variations in the *caliche* described by Whitehead (p. 206) who states the lowermost nitrate is deeply covered, of poorer grade, and contains abnormal amounts of fine sand; the nitrate on the middle slopes is nearer the surface and of maximum grade; and the nitrate at highest levels is of poorer grade.

Despite variations from place to place and despite apparent inconsistencies in descriptions of the variations of the *caliche* both vertically and laterally, it is generally agreed that the *caliche* tends to be the lower part of a zone which contains the bulk of the deposited salts; and that zone does not usually lie on bed rock, but is perched above bed rock on top of an intervening zone of loose detrital material containing very small amounts of the salts. It is likewise established that the salts themselves are vertically zoned with the least soluble salts most abundant on top and the most soluble salts most abundant at the bottom, with the exception that locally the least soluble salts are abundant again in a layer immediately under the nitrate rich layer.

The level of ground water in relation to the *caliche* bed is of significance with respect to the theory of Singewald and Miller. Whitehead (p. 206) specifically states that the *caliche* lies above ground water level. In Tarapaca ground water level is often near

the salar surface, and he mentions (p. 200) the production of commercial salt by evaporation of water that seeps into trenches dug in the salar. He also refers to the efflorescence of nitrate on the surface of the Salar del Carmen east of Antofagasta in sufficient quantity to justify extraction at intervals of four to five years. At Aguas Blancas, however, he says (p. 107) the level of sheet water is 10 or more meters below the surface in minor basins. Semper and Michels, on the other hand, refer to a small pool of water in Aguas Blancas and state only vaguely that water is encountered at shallow depth in numerous wells (p. 375). Brüggen (p. 252) says one of the most striking phenomena of the Salar de Pintados (Tarapaca) is the shallowness of the ground water level which nowhere is deeper than 5 to 6 meters, and which at many places forms swampy areas on the surface. Of course, higher up on the slopes surrounding the salars, ground water level lies at greater depths below the surface, but specific data as to how deep are lacking. Damaging to the theory of Singewald and Miller, Rich regards the fact that it lies below the level of the *caliche* on these slopes.

The competency of the factors postulated by Singewald and Miller to bring about the deposition and concentration of the nitrate from evaporating ground waters is challenged by Rich on the grounds of the width of the nitrate zone and the vertical range of the nitrate. Whitehead (pp. 206 and 207) says the vertical range in Tarapaca and Tocopilla is from a few to perhaps 30 to 40 meters, but in Taltal often exceeds 100 meters. On shallow slopes the width of the nitrate zone ranges up to 3 to 6 kilometers. The magnitude of these lateral extents and vertical ranges would be critical if the deposition of the salts took place only under present ground water conditions and their localization were limited to creep or efflorescence out of the basins of the salars. Perhaps significant are Rich's observations that the deposits occur on surfaces long exposed to undisturbed weathering and that they are lacking where alluvium accumulated recently (p. 201), and Rogers and Van Wagenen's suggestion that the deposition of nitrate "is probably proceeding now in some sections, although in other parts

it has ceased" (p. 10). Equally significant may be Bailey's observation (p. 154) that the nitrate of the Death Valley area has remained localized along the Eocene shore lines and beaches, being carried downward by surface waters as erosion progressed and upward by the capillary flow of evaporating ground water. This nitrate represents the concentration, by evaporation at the surface, of nitrate that was originally deposited by desiccation in the terrace sediments on which it now rests (p. 160). Thus there is the possibility that the ground water conditions were once more favorable for the concentration by evaporation of their nitrate content, and that this concentration has persisted by processes such as those described by Bailey.

Rich recognizes that rich *caliche* layers on the small hills that rise like islands above the level of the salars are not entirely consistent with the Whitehead theory. Not only is the amount of nitrate concentrated on them in proportion to their source area excessive as compared with that on the larger and longer slopes around the salars, but since they represent the summits of their slopes, nitrate generated on them should have moved down the slopes and left these summits bare. An obvious retort would be that the downward movement of nitrate is checked as the nitrate approaches the salar level, but not at all obvious is the reason for such an effective check of the downward movement of the nitrate just short of the salar level, nor why, if such a check exists, the nitrate should not be telescoped at that level so that the greatest, if not the richest, accumulations occur there. Equally perplexing under Whitehead's theory is the statement by Semper and Michels (p. 379) that the richest nitrate occurs on low divides between adjoining basins.

The vertical zoning of sulphate, chloride, and nitrate, in order of increasing solubility downward, is doubtless rightly attributed by Rich to the work of descending waters (p. 202). The source of the nitrate is not explained by Rich's further statement that "the source of the solution from which it (*i.e.* the cemented crust) was deposited appears to have been above rather than below the caliche crust." One is reminded of the analogy of supergene

zoning in ore deposits, that was so magnificently developed in metalliferous deposits in this same portion of Chile. The vertical arrangement of the supergene minerals and their concentration were both the work of solutions that came from above and not from below. But the materials that were concentrated by the descending solutions were not originally brought in by these solutions but were furnished by ascending solutions. So the vertical arrangement of the salts would be just as they are found, irrespective of whether the nitrate was derived from the bed rock itself or from ground waters that penetrated the bed rock.

Another disturbing factor in the distribution of the salts is the coextensiveness of the least soluble salts and the most soluble nitrate over the vertical range of the deposits. Either the sulphates and the nitrates both migrated down the slopes, as postulated for the nitrates by Whitehead, in which event it is not obvious why the sulphates did not lag behind on the upper slopes and the nitrates move ahead of them to the lower slopes; or the sulphates moved up the slopes to overlap the downward migrating nitrates, a most improbable assumption, which if granted would make the upward movement of the nitrates even more plausible.

Still more troublesome to the Whitehead theory is the change in "horizon" of the salts as they descend from the upper slopes to the lower slopes. According to that theory the nitrate is derived from the bed rock volcanics, and moves from its original position as the result of solution, downward migration, and redeposition. The lateral component of that movement has been many times greater than the vertical component; and the lateral component has been at a lower grade than the grade of the bed rock, so that increasing thicknesses of loose, porous *coba* intervene between bed rock and *caliche*. One can understand that solution, downward migration, and redeposition would tend to have a down slope component, if the movement took place immediately above bed rock, but it is not so clear how a down slope component could be effective in raising the salts to increasing distances above bed rock. Rich states the *caliche* is not localized at the top of the

water table but at the lower limit of surface water penetration (p. 203). The surface water causing the repeated solution of the nitrate was that of the occasional light rains and the numerous heavy fogs (Whitehead, p. 207). Such moderate amounts of water would seem to have a more effective vertical component than horizontal component, and the fact that the vertical component was not adequate to keep the salts down to bed rock level would seem to indicate that the lateral component must have been negligible. And if there was a downslope component adequate to perform the work of the Whitehead theory, why did its effectiveness stop short of the salar level instead of debouching nitrate at least on to the margins of the salar flats. Semper and Michels (p. 376) actually describe the opposite condition at Aguas Blancas as follows:

> Whereas in Tarapaca the nitrate is workable almost immediately above the salar, in Aguas Blancas the nitrate is completely replaced by sodium sulphate for some distance above the foot of the slopes. On the gentle ridges which frequently rise 30 to 40 meters above the level of the salars, in Aguas Blancas, everyone acquainted with the caliche of Tarapaca would confidently expect rich nitrate deposits; borings show, however, only sulphates and salt with little admixture of nitrate.

The position of the salt cemented layers on top of the *coba* would imply the operation of some agency with an upward component in connection with the introduction of those salts, even though there was also another agency, surface waters, producing a zoning as a result of differential downward migration of the salts. This otherwise anomalous position of the *costra-caliche* zone is readily understandable if the salts were the product of evaporating ground water.

A review of available observations on the nature of the nitrate deposits and their localization yields conclusions that substantiate the theory of Singewald and Miller and yet presents phenomena that militate against the competency of that theory. The theory of Whitehead, which is concurred in by Rich, circumvents the difficulties of the former theory but runs into equally great difficulties.

The deposits contain sulphates, chlorides, and nitrates, salts of different solubilities. All are salts that accumulate quite generally in arid and desert regions. The Chilean region is unique in the great quantities of nitrate that have accumulated. Most theories have assumed a special or uniquely rich source of nitrates in this region without specific proof of the peculiar efficacy of the assumed source. Whitehead's theory assumes, but does not give direct proof, that the volcanic tuffs were the source of the nitrate. The assumption is based on a distribution of the nitrate which he believes is compatible with and a natural result of this assumption. In other words, a source is inferred from an effect. But all features of the effect do not seem to be in harmony with the mechanism of the effect. Three features that are not an obvious result of that mechanism are: (1) the areal coextensiveness of the least soluble and the most soluble salts; (2) the supposed downslope movements of the salts at lower grade than bed rock grade, raising them to increasing elevations above the bed rock from which it is assumed they were derived and requiring their flow on a loose, porous substratum; (3) the lack of a marked concentration of the nitrate at the base of the downslope, which is the terminus of their assumed course. The zoning of the salts is well explained by differential redeposition by descending surface water and moisture acting with a vertical component only. It is a phenomenon that neither supports nor refutes either Whitehead and Rich's theory nor Singewald and Miller's theory.

The marked tendency of the salts to occur in the salars and on the surrounding slopes suggests a common origin. The salars represent the usual ultimate concentrations of the soluble salts of the waters of a desert region. That the salts are not more closely restricted to the salar surfaces, suggests that they are not entirely the result of evaporation of surface waters on the salars, but were formed from evaporating ground waters below the surface. Such an origin would explain the marooning of the salts above the loose, porous *coba*. It would explain the deposition of nitrate at elevations higher than the salar surface. Deliquescence and ef-

florescence of the most soluble nitrate would explain the usual absence of nitrate on the salars themselves. The excrescence of nitrate on the Salar del Carmen is not a refutation of the ground water theory, but is an exception in support of it. Difficulties that this theory has to face are: (1) the depth of ground water at present which is greater than that of the deposits supposedly derived from it; and (2) the magnitude of efflorescence and creep required by the absence of nitrate in the salars.

The conclusion appears to be inescapable that both theories are based more on argument and inference than on demonstration. The facts are still too incompletely known to definitely prove or disprove either theory. Before a well established and convincing explanation of the origin of these deposits can be arrived at, much more comprehensive facts must be accumulated. The discovery, development, and extraction of this valuable product do not require such an exhaustive study of the geology of the region. The industry will probably never provide the necessary geologic data. It is a problem of scientific interest rather than of economic importance. Its solution requires a long and costly scientific geologic investigation under extremely difficult physical conditions. Until such personnel and such resources may be directed to the problem, it must inevitably remain in the realms of speculation and argument rather than in the field of demonstration. The last word on the genesis of Chilean nitrate may never be written for lack of such an approach.

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JOSEPH T. SINGEWALD, JR.

THE JOHNS HOPKINS UNIVERSITY,
June 4, 1942.

AUTHOR'S REPLY.

Sir: The comments by Cederstrom [1] and McKnight [2] both raise a pertinent question as to the fact that secondary enrichment in some deposits is definitely restricted to a narrow vertical range controlled by water level. The outstanding examples of this situation in the United States are the thin and shallow chalcocite zones in the Appalachian copper deposits, especially of Virginia and Tennessee, where a few feet of intense enrichment was found beneath an iron cap and on top of primary sulphides. It seems clear that enrichment in this area is related more to the lateritic type of weathering than to the arid pattern and it is to be presumed that this enrichment occurred under conditions of plentiful moisture and a definite water table. Probably still more important, however, is the fact that the crystalline rocks in which these deposits occur are not easily soluble and, presumably, as evidenced in other areas, such rocks lack the right kind and amount of porosity to permit the gravitational mechanism to function.

As to other areas, supergene enrichment in many districts is a notoriously vicarious affair extending to hundreds of feet in some places, with preservation of unaltered sulphides near the surface at other places. This is emphatically true at Balmat, N. Y. The quotation from Marsh regarding Bingham states that the average depth of enrichment is 600 or 700 feet, *but the maximum is 2200 feet!* Lindgren's data for Rio Tinto, 200 feet to 1500 feet at

[1] Cederstrom, D. J.: Differential density of ground water in ore deposition. Disc. ECON. GEOL. 37: 524, 1942.

[2] McKnight, E. T.: Differential density of ground water in ore deposition. Disc. ECON. GEOL. 37: 424–426, 1942.

various places, shows a similar wide range, and instances could be multiplied.

Respecting mathematical treatment and laboratory checks on the theory, I frankly distrust my ability to do the one and have not time or facilities for the other. The main object of the present paper has been to point out that gravitational differences in equivalent solutions of common substances are significant, and, by actual determinations, are duplicated in natural mine water.

JOHN S. BROWN.

REVIEWS*

X-Ray Crystallography. By M. J. BUERGER. Pp. xix + 531; Figs. 252. John Wiley & Sons, Inc., New York, 1942. Price, $6.50.

This is a most welcome book for both teachers and research workers in x-ray crystallography. Much of the material has heretofore been available only in widely scattered papers in various journals, while a considerable portion of it appears in print for the first time.

A feature of the book that will be appreciated by many teachers and students alike is the straightforward analytical type of proof used. Many students become interested in x-ray crystallography through mineralogy, which in turn they have approached through geology. For these students with a minimum of physics as a background the analytical proofs are especially welcome.

The illustrations have been carefully prepared and each illustrates its point well. The thirty-four tables bring together much valuable data and their use eliminates many calculations.

The name "X-Ray Crystallography" is more general than the text. The author limits his discussion to the rotating crystal methods with emphasis on those of the moving film, and omits the Laue and the "powder" methods of crystal analysis. These two should be included in a general treatment of the subject.

The treatment of the equi-inclination Weissenberg method is excellent and brings together for the first time an adequate discussion of this most important method. However, the discussion of the normal-beam Weissenberg method is mostly of historical interest and its extended treatment may give rise to some confusion on the part of the student.

The publisher has done an excellent job and with the author should be congratulated on bringing out this much-needed book.

C. S. HURLBUT, JR.

HARVARD UNIVERSITY.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

Seismology. By PERRY BYERLY. Pp. 256; Figs. 57. Prentice-Hall Inc., New York, 1942. Price, $4.65.

Here is an attempt to cover *in brief* the field of earthquake seismology. The author has treated applied seismology or seismic prospecting in another volume of this series and the general subject of earthquakes, the theory of earthquake waves and the theory of the seismograph have been treated extensively in other books and articles.

The first part of the book is on the subject of earthquakes and requires little technical knowledge. Its chapters touch on Elasticity and Plasticity, Earthquake Vibrations, Immediate Cause of Earthquakes, Underlying Causes of Earthquakes, Effects of Earthquakes, Distribution of Earthquakes, Great Earthquakes.

The second part of the book presupposes readers with some preparation in mathematics and physics and presents, in greater detail, material on The Seismograph (the different types and methods of recording), Elastic Waves, Paths of Waves and Travel Time Curves, Location of Epicenters, and Seismograms.

Photographs are from the file of the Berkeley seismograph station and, with one exception, leave something to be desired in reproduction. However, the other figures and maps are clear and readable.

BERNARR BATES, Lt., U.S.N.R.

Geomorphology, Systematic and Regional. By O. D. VON ENGELN. Pp. xxii and 655; Figs. 372, Pls. 7. Macmillan Co., New York, 1942. Price, $4.50.

Publication within the last five years of at least six books in English on physiography and geomorphology might lead one to suppose that this field is adequately supplied with modern texts. Professor von Engeln's volume successfully demonstrates the fallacy of that supposition. This work is immediately removed from the commonplace by its content, organization, and illustrations.

Attractive pencil sketches of William Morris Davis and Walther Penck, facing each other on opposite pages, quickly and effectively establish the major theme. Analysis of the opposing concepts of Davis and Penck and discussion of the fluvial geomorphic cycle follow introductory chapters providing general background. Few American writers are as competent as von Engeln to present a summary and evaluation of Walther Penck's work. Aside from the recently published symposium of the Association of American Geographers (Annals, vol. 30), of which he was the organizer, no other work in English gives such a simple, complete, and sympathetic digest of the Penckian philosophy. Although the author is convinced of

the soundness of the American-British approach, he feels that the German school has significant contributions to make. As he presents the matter, most readers will feel inclined to agree. By analyzing the German viewpoint in a competent affirmative manner this book points the way to a partial blending of concepts from which a more vigorous geomorphic discipline can be molded. On that point alone this book is a notable contribution.

More commonplace topics also receive treatment, and considerable space is devoted to fault forms, the fluvial cycle in domed and folded regions, karst topography, glaciation, vulcanism, coral reefs, coastal features, and the desert geomorphic cycle. The content of the chapters on "Relief of the Ocean Bottoms," "Waterfall Sites," and "Karst Topography" are of more than usual interest. The "History of the Folded Appalachians" is one of the most lucid and informative chapters in the entire book. It presents an up-to-date well-rounded analysis of this complex problem and gives a clear concept of Appalachian geomorphology which will appeal particularly to those who have not been able to keep pace with the latest developments in this classic field. The author's classification of geomorphic units should facilitate future physiographic descriptions, and geomorphologists will recognize the soundness of his discussion of grade and accordant summits. Careful attention is paid throughout to foreign terminology, and an enviable acquaintance with the foreign literature is displayed.

Not the least among the attractive features of this volume are the abundant illustrations. A successful effort has been made to obtain new illustrations, which give the book an exceptional vitality. The frontispiece in natural color is excellent. Works to which reference is made are assembled in a composite list at the back adjoining the index. This is supplemented by selected references at the end of each chapter, effectively subdivided into classical and recent groups.

Although organization is one of the book's distinctive features, it is not likely to appeal to most readers as wholly satisfactory. The arrangement followed requires needless repetition, disperses genetically related features under inappropriate headings, and produces anomalous associations. For example, rock weathering is relegated to Chapter XIV near the middle of the book following consideration of erosion and factors of rock hardness. Discussion of rock glaciers, felsenmeer, soil stripes, and landslide topography is included with propriety in the chapter on weathering, but closely allied features, such as talus, landslides, rock falls, and solifluction are treated in a preceding chapter on "Interruptions of the Fluvial Geomorphic Cycle. . . ." This latter chapter also contains a discussion of alluvial fans and deltas, while the preceding chapter on ". . . the Fluvial

Cycle on an Oldland" includes consideration of incised and intrenched meanders, certain types of natural bridges, and gorges. Many other examples of peculiar association and arrangement will be apparent to the careful reader. A minor criticism is the disconcerting use of new terms in the captions of illustrations before those terms are introduced in the text. Occasionally this cannot be avoided, but a minimum of such occurrences is desirable. The book is not without inconsistencies, as for example that furnished by the caption of Figure 40, p. 102, describing the Ep-Algonkian erosion surface in the Grand Canyon as a plain of marine erosion—a conclusion not usually supported by anyone who has studied that surface in detail—and a statement on p. 544 to the effect that widespread ancient plains of marine erosion are actually improbable.

Not all aspects of controversial subjects can be given consideration in a work of this kind. However, many readers may feel that the author would have done well to use the foreword of Chapter XIX, in which he notes the impossibility of presenting all opinions on debatable topics, as a general foreword to the book. Students of desert forms, coastlines, and shore processes, among others, may not be entirely satisfied with the treatment of those subjects, but they should recognize that it is the author's privilege to present his evaluation of these topics as long as it is clearly indicated as such.

It is difficult to escape the impression that this book will appeal more to the experienced geologist and advanced student than to those whose knowledge is elementary. There is no question but that it is a notable contribution destined to take its place among American books of recognized distinction. No well-informed geologist or geographer can neglect reading at least parts of this volume if he wishes to keep abreast of modern developments in geomorphology.

ROBERT P. SHARP.

UNIVERSITY OF ILLINOIS.

BOOKS RECEIVED.

WILLIAM E. BENSON.

Aerial, Geological and Geophysical Survey of Northern Australia. *Additional papers of the series of reports published at Canberra.*

Western Australia Reports.

No. 16. **The Tambourah and Western Shaw Mining Centres, Pilbara Gold-Field.** K. J. FINUCANE. Pp. 7; Pls. in color 2.

No. 20. **The Warrawoona Area, Pilbara Gold-Field.** F. H. JONES. Pp. 10; Pls. in color 3.

No. 25. **Recent Gold Discoveries near Wyman's Well, Pilbara Gold-Field.** K. J. FINUCANE. Pp. 3; Pl. 1.

No. 35. **Geophysical Report on the Kookynie Area, North Coolgardie Gold-Field.** E. L. BLAZEY, J. M. RAYNER AND P. B. NYE. Pp. 8; Pl. 4.

No. 36. **Geophysical Report on the Wiluna Area, Wiluna (Pt. 1, Electro-Magnetic Surveys).** E. L. BLAZEY, J. M. RAYNER AND P. B. NYE. Pp. 8; Pls. 6.

No. 37. (*a*) **Notes on the Geology of the Big Bell Area.** K. J. FINUCANE. Pp. 2; (*b*) **Geophysical Report on the Big Bell Area.** E. L. BLAZEY, J. M. RAYNER AND P. B. NYE. Pp. 4; Pls. 2.

Northern Territory Report.

No. 20. **The Eastern Portion of the Arltunga Area, Eastern MacDonnell Ranges District.** P. S. HOSSFELD. Pp. 13; Pls. 2.

Los Yacimientos Minerales de Bolivia. F. AHLFELD. Pp. 282; Figs. 54; Map 1. Ministerio de Economia Nacional. Dir. Gen. de Minas y Petroleos. La Paz, 1941. Price, $3.00.

Instituto de Pesquisas Tecnologicas de São Paulo. São Paulo, 1941.

Relatorio Correspondente Ao Exercicio de 1940.

Bol. 29. **Dados Experimentais do Freijo.** F. A. BROTERO. Pp. 9; Figs. 5; **Contraplacado Nacional para Aviacão.** A. VIEIRA. Pp. 10; Figs. 7; **Cálculo de Longarinas em Caixão.** E. DE M. ALVARENGA. Pp. 18; Figs. 7.

Ministerio de Justicia e Instruccion Publica. Publicaciones Inst. de Fisiog. y Geol. Rosario, 1940.

B–1940. **Cronica Bibliografica. Mineral y Mineria Geologia-Petrografia Geografia-Paleontologia.** A. CASTELLANOS AND P. PASOTTI. Pp. 112.

VIII. **A Propósito de los Géneros Plohophorus, Nopachthus y Panochthus, Pt. 2.** A. CASTELLANOS. Pp. 135; Figs. 86.

Instituto Nacional de Tecnologia. Rio de Janeiro, 1941.

As Argilas Descorantes e sua Ativação. Technologia, Análises e Aplicações. Y. E. STOURDZÉ. Pp. 103.

Dosagem do Fosforo pelo Método de N. v. Lorenz. Y. E. STOURDZÉ. Pp. 40.

Sobre Uma Substancia Graxa do Litoral do Piauí C. ROLIN. Pp. 16.

Desenvolvimento da Tecnica Para a Determinação do Volframio em Seus Minerios. A. DE L. CANTIÇÃO. Pp. 13.

Olga-Mattagami Area, Abitibi Territory. P. E. AUGER. Quebec Dept. Mines. Geol. Rep. 10. Pp. 19; Map 1; Pls. 3. Quebec, 1942.

La Géologie de Québec. Vol. I. Bibl. et Index. Québec Service des Mines. Pp. 180. Québec, 1941.

Some Haulage Safety Devices for Use on Grades, Slopes, and Inclined Shafts. G. W. GROVE, S. H. ASH AND E. J. RISTEDT. Pp. 44; Figs. 51. U. S. Bur. Mines, Washington, 1942. Price, 10 cents.

U. S. Geol. Surv., Washington, 1941 and 1942. Bulletins:

917–D. **Tertiary Deposits of the Eagle-Circle District, Alaska.** J. B. MERTIE, JR. Pp. 51; Geol. map; Index map. Price, 15 cents.

926–B. **Geology of the Gerstle River District, Alaska.** F. H. MOFFIT. Pp. 53; Figs. 3; Pls. 10. Price, 35 cents.

931–C. **Tin Deposit at Majuba Hill, Pershing County, Nevada.** W. C. SMITH AND V. P. GIANELLA. Pp. 16; Index map; Geol. maps 2. Price, 25 cents.

931–E. **Tungsten Deposits in the Sierra Nevada Near Bishop, California.** D. M. LEMMON. Pp. 25; Figs. 3; Pls. 7. Price, 35 cents.

931–F. **Nickel Deposits of Bohemia Basin and Vicinity, Yakobi Island, Alaska.** J. C. REED AND J. V. N. DORR 2D. Pp. 33; Index map; Geol. maps 4. Price, 70 cents.

931–G. **Chromite Deposits of Kenai Peninsula, Alaska.** P. W. GUILD. Pp. 36; Figs. 5; Pls. 8. Price, 50 cents.

931–I. **Nickel Deposit Near Riddle, Douglas County, Oregon.** W. T. PECORA AND S. W. HOBBS. Pp. 21; Figs. 3; Pls. 2. Price, 20 cents.

931–J. **Quicksilver Deposits in the Steens and Pueblo Mountains, Southern Oregon.** C. P. Ross. Pp. 31; Fig. 1; Pls. 6. Price, 40 cents.

931–L. **Tin Deposits of Northern Lander County, Nevada.** CARL FRIES, JR. Pp. 15; Figs. 3; Pl. 1. Price, 20 cents.

931–M. **Manganese Deposits in the Nevada District, White Pine County, Nevada.** R. J. ROBERTS. Pp. 23; Figs. 5; Pls. 3. Price, 25 cents.

931–N. **Quicksilver Deposits of the Opalite District, Malheur County, Oregon and Humboldt County, Nevada.** R. G. YATES. Pp. 29; Figs. 3; Pls. 7. Price, 60 cents.

931–O. **Nickel Deposit Near Gold Hill, Boulder County, Colorado.** E. N. GODDARD AND T. S. LOVERING. Pp. 13; Index map; Geol. maps 2. Price, 30 cents.

931–P. **Mica-Bearing Pegmatites of New Hampshire.** J. C. OLSON. Pp. 40; Figs. 8; Pls. 3. Price, 25 cents.

931–Q. **Quicksilver and Antimony Deposits of the Stayton District, California.** E. H. BAILEY AND W. B. MYERS. Pp. 27; Figs. 4; Pls. 4. Price, 40 cents.

932–B. **Geophysical Abstracts 105, April–June, 1941.** W. AYVAZOGLOU. Pp. 84. Price, 10 cents.

932–C. **Geophysical Abstracts 106, July–Sept., 1941.** W. AYVAZOGLOU. Pp. 37. Price, 10 cents.

933–A. **Mineral Industry of Alaska in 1940.** P. S. SMITH. Pp. 102; Figs. 3; Pl. 1. Price, 35 cents.

SOCIETY OF ECONOMIC GEOLOGISTS

ANNUAL MEETING 1942–43.

After due consideration of the war-time difficulties caused to our hosts by the proposed meeting of the Society of Economic Geologists, the Geological Society of America and affiliated societies at Ottawa in celebration of the centenary of the Canadian Geological Survey's founding, the meeting has been cancelled by common consent of all participants.

The Council of the Society of Economic Geologists has instead decided to follow its customary biennial practice of meeting jointly with the American Institute of Mining and Metallurgical Engineers in New York City, February 14–18, 1942. The program will be especially directed to problems raised by the war. Papers planned for the Ottawa meeting may be offered for the New York meeting, and members and others interested are requested to submit additional papers for a place on the program. The closing date for considering abstracts will be January 1. Forms for abstracts will be mailed by any of the undersigned members of the Program Committee upon request.

M. E. WILSON
Geological Survey of Canada
Ottawa, Ont., Canada

DAVID G. THOMPSON
U. S. Geological Survey
Washington, D. C.

H. C. GUNNING
University of British Columbia, Dept. of Geology
Vancouver, B. C.

CHAS. H. BEHRE, JR.
Columbia University, Dept. of Geology
New York, N. Y.

SCIENTIFIC NOTES AND NEWS

The editor and publishers of the Journal regret that it is necessary to complete the 37th volume by combining the last two numbers. This is not completely unprecedented since Numbers 4 and 5 were combined in Volume 16. Most geologists are now engaged in war work of some kind with the time necessary to prepare scientific papers extremely limited for all of them, and we do not have the usual number of manuscripts on hand. Nevertheless we are extremely sorry that the indulgence of our subscribers must be asked.

To conform with postal regulations, the Index and Volume Contents will be published as Number 8 and mailed late in December.

CLYDE P. ROSS has requested publication of the following explanation of Fig. 1 in his paper on the geology of quicksilver deposits (ECON. GEOL., 37: 439–465).

"The black areas are quicksilver mining districts (drawn to scale). The crosses represent minor prospects and reported occurrences, some of which may not be actual deposits or may be inaccurately located."

TRUMAN H. KUHN has resigned his position as geologist of the Magma Copper Co. to accept an assistant professorship of geology at the Colorado School of Mines.

B. N. COOPER and W. R. BROWN have been added to the staff of the Virginia Geological Survey. Dr. Brown is engaged in studies of the mineral resources of piedmont Virginia and Dr. Cooper is in charge of studies on the stratigraphy, structure and nonmetallic mineral resources in the southern half of the Appalachian Valley in Virginia. R. S. EDMUNDSON, for some years a staff geologist, is in charge of similar studies in the northern half of the Valley.

E. Y. DOUGHERTY, whose headquarters are at Rapid City, S. Dakota, is district engineer for the U. S. Bureau of Mines for the Dakotas, Iowa and Nebraska.

The Petroleum division of the A.I.M.E. held meetings in Los Angeles, October 15–16 with the cooperation of the Southern California section, and with the cooperation of the Gulf Coast Section in Austin, Texas, October 29–31. The annual fall meeting of the Institute of Metals and Iron and Steel Divisions was held in Cleveland, October 12–14.

The GEOLOGICAL SOCIETY OF AMERICA has cancelled the Annual Meeting which was to have been held in Ottawa. The regular Annual Meeting of the Society will be held on December 29 at the Headquarters of the Society and will be limited to the usual business sessions.

The Metals and Minerals division of the Board of Economic Warfare reports that J. T. SINGEWALD, JR. has returned to Johns Hopkins University from the Argentine, where he was investigating expansion of production of tungsten, mica and beryl; WILLIAM BURNS is in Colombia, accompanied by QUENTIN SINGEWALD; DEAN FRASCHE has returned from the Congo and the west coast of Africa where he has been investigating minerals, particularly tin, tantalum and chrome and ANTON GRAY has returned from the Congo and Northern Rhodesia; DAVID GALLAGHER has returned to Mexico where he is investigating mercury deposits for the Metals and Minerals division and the U. S. Geological Survey.